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ENVIRONMENTAL GUIDE TO THE VIRGINIA CAPES OPERATING AREA

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ABSTRACT

The general oceanography of the of the Virginia Capes (VACAPES) area is discussed with particular emphasis on near-surface thermal structure of water masses and oceanic fronts. Warm, saline Gulf Stream Water, identified by temperature equal to or greater than 15° Celsius (C) at the 200-meter (m) level, is characterized by mean monthly sea surface temperature (SST) and sonic layer depth (SLD) ranging from 21°C and 78m, respectively, in winter to 28°C and 25m in summer. Slope Water, identified by temperatures between 9° and 15°C at the 200-m level, is characterized by a temperature inversion in spring and mean monthly SST and SLD ranging from 11°C and 203m, respectively, in winter to 25°C and 6m in summer. Relatively fresh Shelf Water, found on the Continental Shelf between the 30-m and 200-m isobaths, is characterized by a positive in-layer temperature gradient in winter and mean monthly SST ranging from 7°C in winter to 25°C in summer. SLD is at the bottom in winter and is 3m in summer. Two major oceanic fronts occur in the VACAPES area: the northern edge of the Gulf Stream separating Gulf Stream Water from Slope Water and the slope front separating Shelf Water from Slope Water. The northern edge is characterized by mean seasonal temperature differences across the front ranging from 6°C in winter to 2°C in summer, frequent cold filaments and multiple temperature gradients at the surface, and temperature inversions throughout the year. The slope front is characterized by a mean seasonal temperature difference across the front ranging from 5°C in winter to nil in summer (when surface heating masks the front) and a well-formed temperature gradient from spring through autumn. Water mass interaction, in the form of Gulf Stream meanders, eddies of Gulf Stream origin in Slope Water, and entrainment of Shelf Water by the Gulf Stream cause the area to be complex oceanographically.

by

ALVAN FISHER, JR.

FOREWORD

Knowledge of oceanographic conditions within an area is of prime importance to operational Fleet units. Weapon choice, screen formation, search and rescue operations, and replenishment are all greatly affected by the ocean environment. This report gives an overall perspective of the oceanography of the Virginia Capes Operating Area. It is intended to provide information for planning and to aid on-the-scene commanders in recognition of oceanographic features.

P. V. Purkrabek

P. V. PURKRABEK
Captain, U. S. Navy
Commander

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I. INTRODUCTION

Many Fleet operations are sensitive to the environment. Effectiveness of a destroyer screen may depend critically upon the local thermal structure, the possibility of underway replenishment upon sea state, and air operations upon visibility. In all cases intelligent understanding of the natural environment leads to more successful operations.

The objective of this report is to provide detailed information concerning the physical oceanography of the Virginia Capes Operating Area (VACAPES). This information can be utilized in several ways:

...A Task Group Commander can better deploy his forces and make more accurate tactical decisions if he has a knowledge of the local environment.

...Evaluations of detection or weapon systems often require specific thermal structure characteristics. This report provides information that can be utilized in deciding where and when an evaluation should be conducted in the area.

...A meteorologist tasked with predicting environmental conditions in the Virginia Capes will find the description of typical thermal structure characteristics a useful guide.

Information contained in this report is based mainly on data collected over a 4-year period (1967-1971) using an airborne radiation thermometer (ART) and air dropped bathythermograph (AXBT) system aboard an EC-121K aircraft under the operational control of the Naval Oceanographic Office (NAVOCEANO), and shipboard expendable bathythermograph (SXBT) systems aboard research, Coast Guard, and naval vessels. In some cases data were sufficient to calculate mean and 95-percent confidence limits of thermal features within specific water masses on a monthly basis; in other cases the lack of data precluded such details. A bibliography of articles pertaining to the physical oceanography of the VACAPES area is included for the reader interested in more detailed descriptions than given here.

II. GENERAL DESCRIPTION

The VACAPES region (figure 1) is an area where interaction among three basic water masses causes considerable spatial and temporal variability in the thermal structure characteristics. This is well illustrated by sudden shifts in the northern edge of the Gulf Stream with its accompanying overrunning and meandering. Because the VACAPES area is a favored location for storm formation, the surface layers of water are often subjected to sudden increases in wind and wave forces which in turn produce rapid modifications in layer depth. Circulation

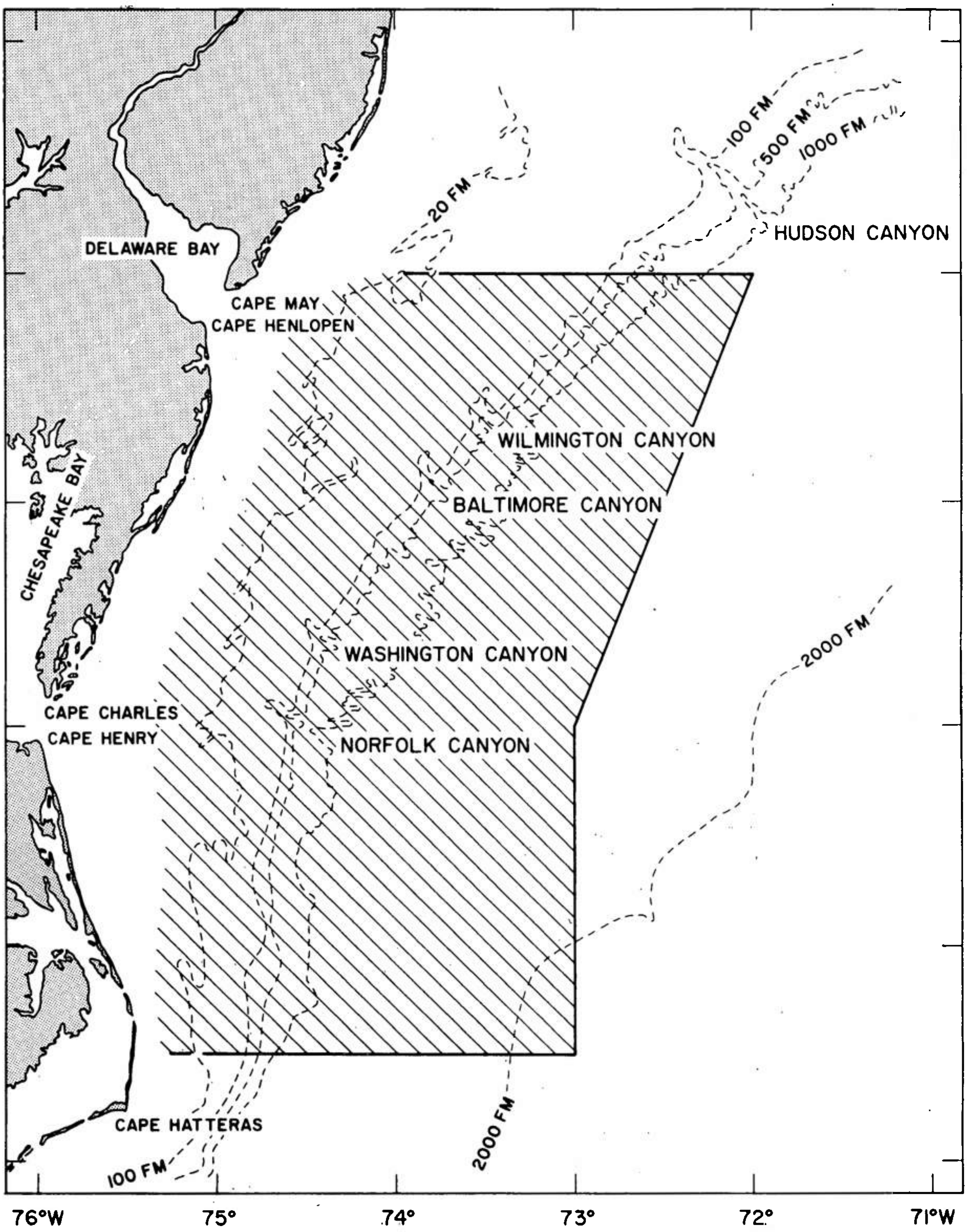

Figure 1 Virginia Capes area

is complicated by a wide range in bottom depth and the presence of land as the western boundary of the area. The proximity of land also leads to sudden temperature change in some seasons owing to advection of cold, unmodified air from the continent.

Three basic water masses occur in the VACAPES area: Shelf Water, Slope Water, and Gulf Stream Water. Each water mass has unique thermohaline relationships which permit positive identification. Water temperature profiles alone often provide reasonably accurate water mass identification. For example, a bathythermograph (BATHY) report with a sea surface temperature of 14.2°C and a nearly isothermal layer of 14.5°C from 125 to 250 meters could occur only in Slope Water during winter. Sea surface temperature reports are helpful, but less reliable, for water mass identification. A ship report of 22°C received the same day as the above BATHY report could have occurred only in the Gulf Stream. However, surface temperature values in summer are not as reliable as in other seasons because of widespread surface heating.

Two major water mass boundaries (frontal zones, oceanic fronts) are found in the area: (1) the northern edge of the Gulf Stream separating Slope and Gulf Stream Waters and (2) the slope front separating Shelf Water from Slope Water.

The ocean bottom in the Virginia Capes area is divided into three major physiographic regimes: Continental Shelf, Continental Slope, and Continental Rise. The boundaries of these regimes are shown in figure 2.

The Continental Shelf is a moderately smooth plain broken by many relatively small irregularities (sand waves, channels, terraces, coral mounds) generally less than 10 meters (m) in relief. Width and slope on the shelf vary from 190 kilometers (km) and 3' south of New York City to 23 km and 7' off Cape Hatteras. The transition zone (termed shelf break) between the Continental Shelf and the Continental Slope offshore occurs at a depth of 160 m off Cape May, 120 m off Norfolk, and 60 m off Cape Hatteras. Sediment is predominantly sand with occasional patches of gravel. Grain size of the sand is somewhat coarser near the shelf break than in shallower water inshore.

The Continental Slope is very irregular and is cut by four submarine canyons (from north to south: Wilmington Canyon, Baltimore Canyon, Washington Canyon, and Norfolk Canyon). These canyons have deep channels extending seaward. Average slope of the Continental Slope is 4° from Cape May to Cape Henry and 4° to 5° from Cape Henry to Cape Hatteras. Bottom sediments are generally silt-clay and sandy silt, although outcrops of bedrock occur in the canyons.

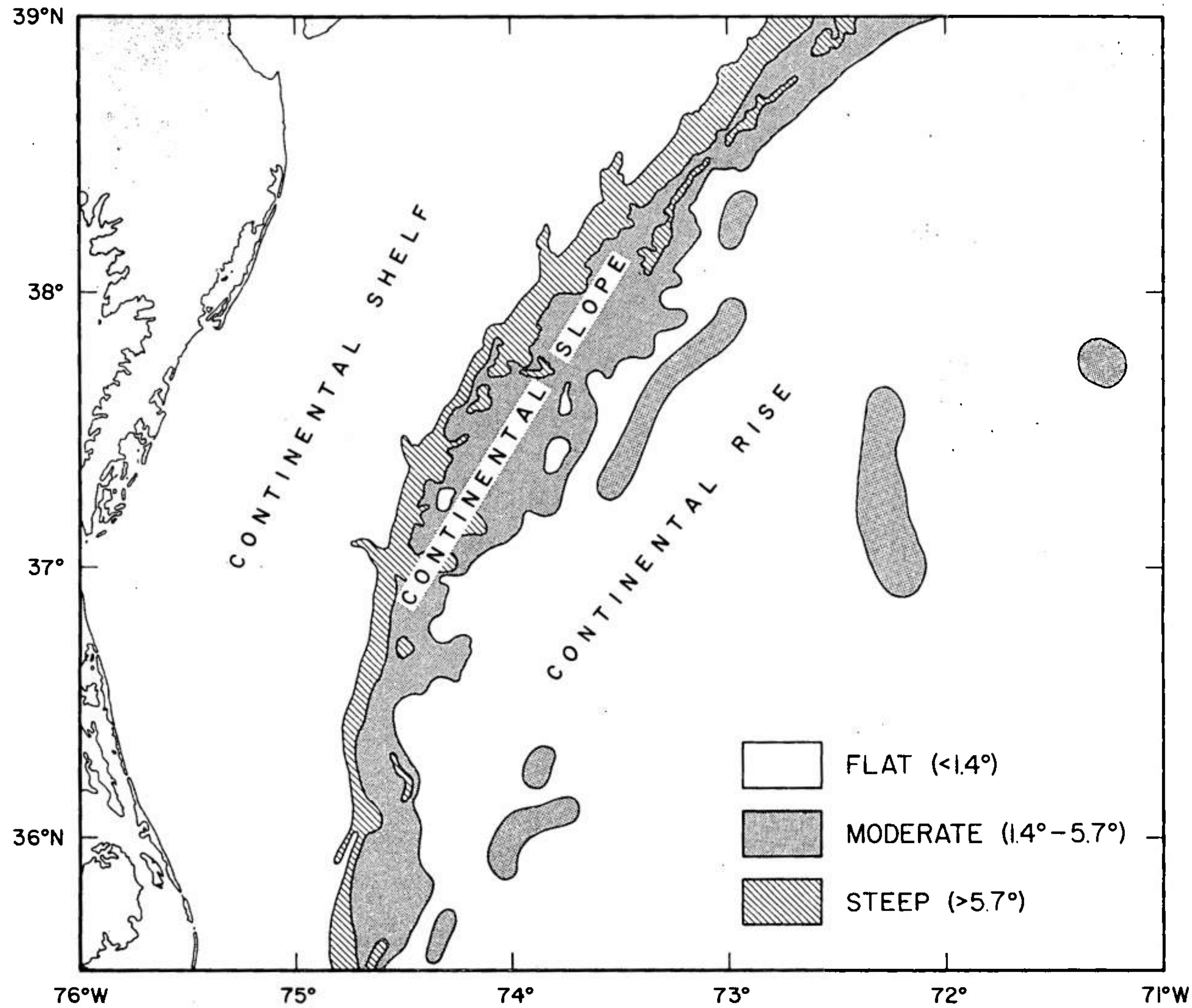

Figure 2 Bottom slope regimes

The Continental Rise extends seaward from the base of the Continental Slope to the abyssal plain of the North American Basin. Relief is usually less than 40 m but may be as great as 300 m. Slope of the rise is about 30'. Bottom sediment is mostly terrigenous (land derived) and ranges from sandy silt at the base of the Continental Slope to silt and red clay farther offshore. Sand beds are generally found near the mouth of the submarine canyons.

The distribution of bottom sediments in the VACAPES area is shown in figure 3. Although most of the data were collected in shallow water, the accuracy of identification and delineation of sediment types is about the same throughout the area because sediment is less variable in deep water. Considerable difference in bottom reflectivity will occur between some areas; sand and gravel bottoms are considered good acoustical reflectors, whereas mud is a poor reflector. The acoustical properties of areas with mixed composition vary according to the ratio of mud to sand.

III. WATER MASSES

Thermal characteristics of each water mass were determined from examination of several thousand XBT traces collected within the VACAPES area. Temperature at depth was used to differentiate water masses, because relatively little seasonal change extends below the surface layer. For example, Slope Water has a variance of 0.6°C at the 200-m level compared to a variance of 32.0°C at the surface.

Seasonal changes in water temperature generally lag those of the overlying atmosphere; consequently, in the area of the study, the seasons are defined as follows: winter (January-March), spring (April-June), summer (July-September), and autumn (October-December).

Figures 4 through 7, along with figures 8 and 9, illustrate typical seasonal positions of the three water masses found in the VACAPES area, their mean monthly sea surface temperature (SST), and their mean monthly sonic layer depth (SLD). Areas of overrunning, where lighter water rides over heavier water, are indicated by hatching. In these areas anomalous vertical temperature profiles will be found: shallow layer depths, positive near-surface thermal gradients, and other characteristics that may affect sound ranging. The following paragraphs give more detailed descriptions of the thermal characteristics of the individual water masses.

A. Gulf Stream Water

North Atlantic Central Water (NACW) is the major water mass in the upper layer of the North Atlantic. The Gulf Stream, which represents the western boundary of the NACW, is warmer and less saline at the surface than NACW to the east of the VACAPES area. To distinguish between the two water masses, the westernmost is called Gulf Stream Water in this study while the water to the east (and outside the VACAPES area) is called Sargasso Water.

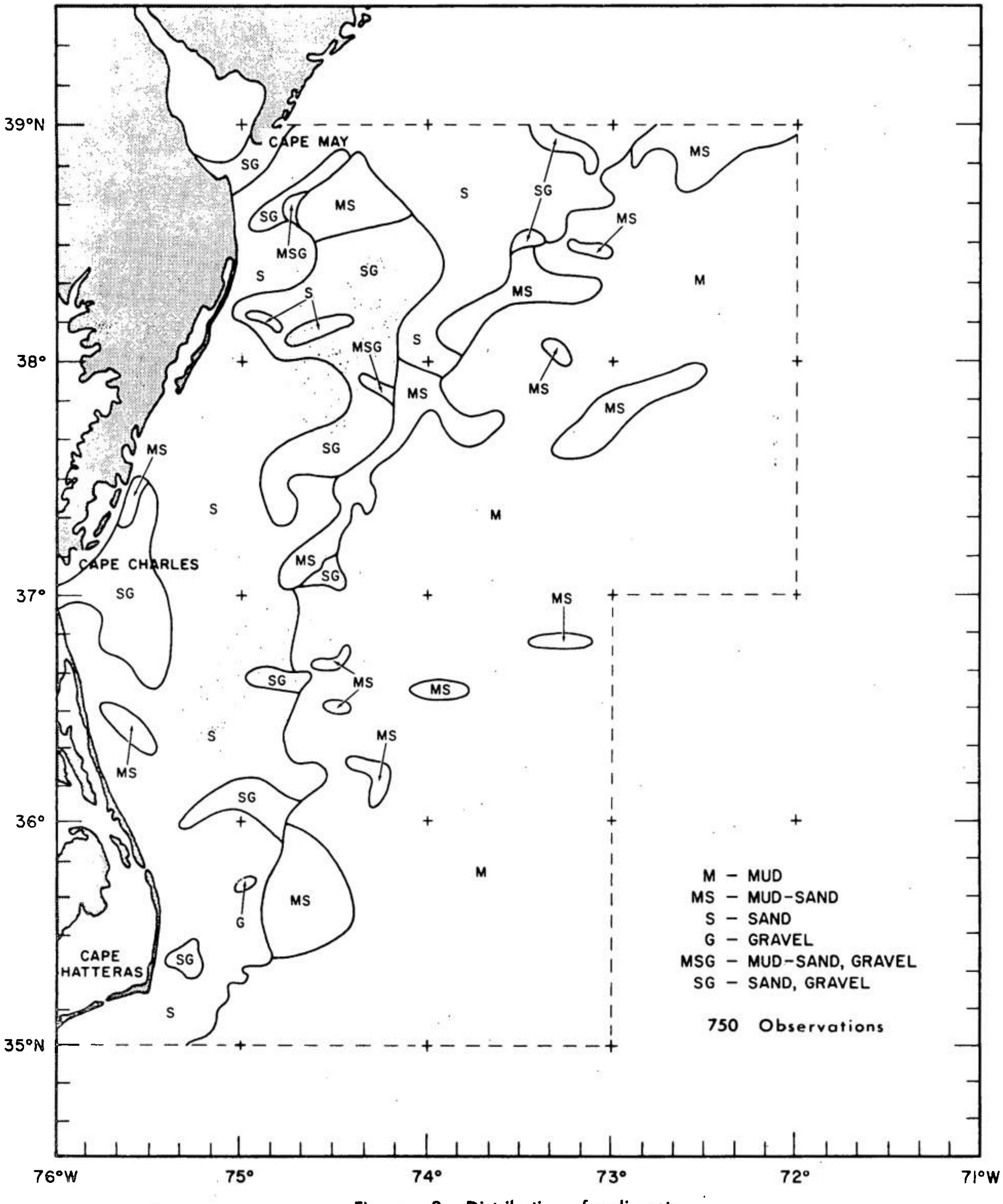

Figure 3 Distribution of sediments

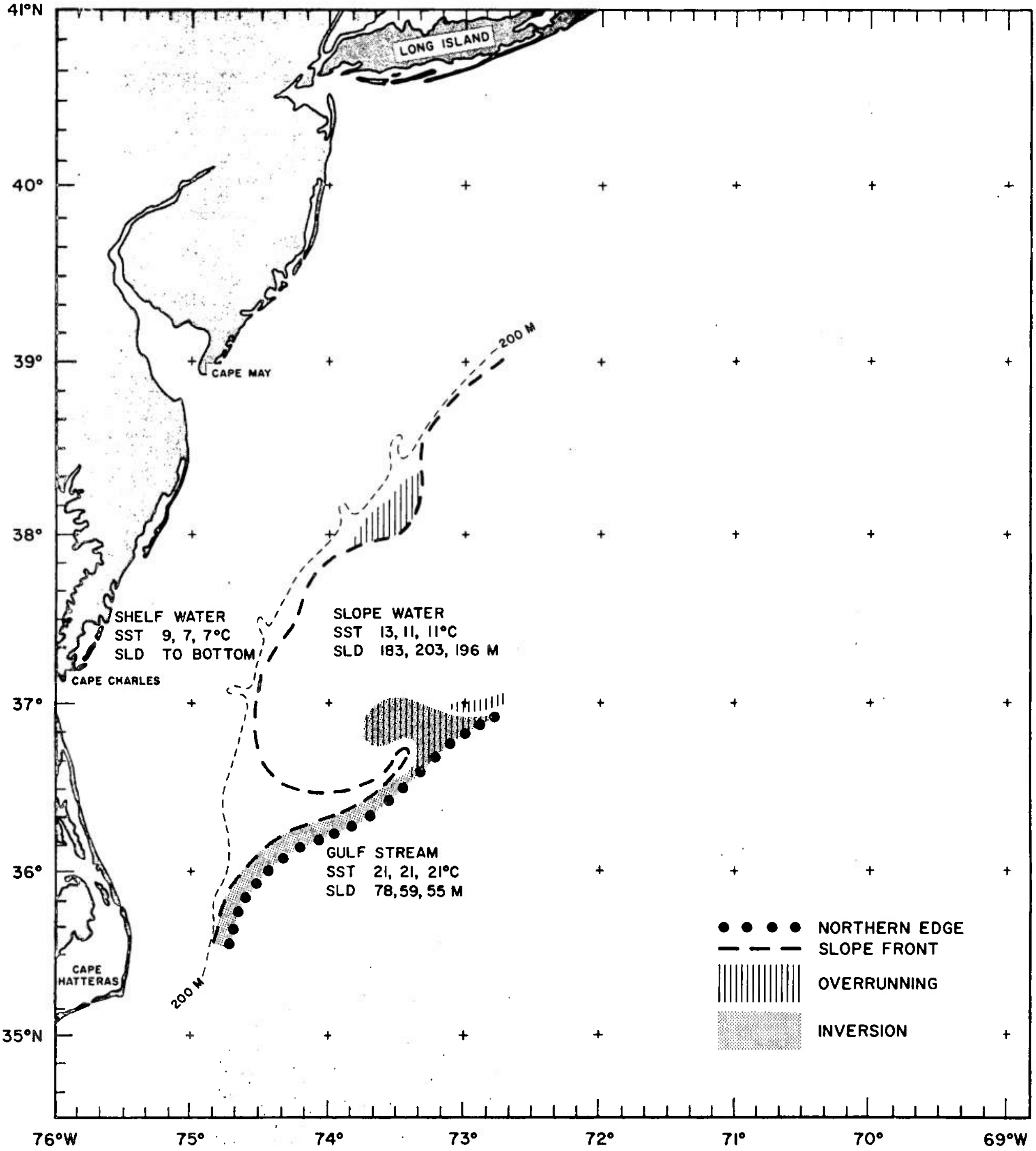

Figure 4 Winter thermal structure (January through March)

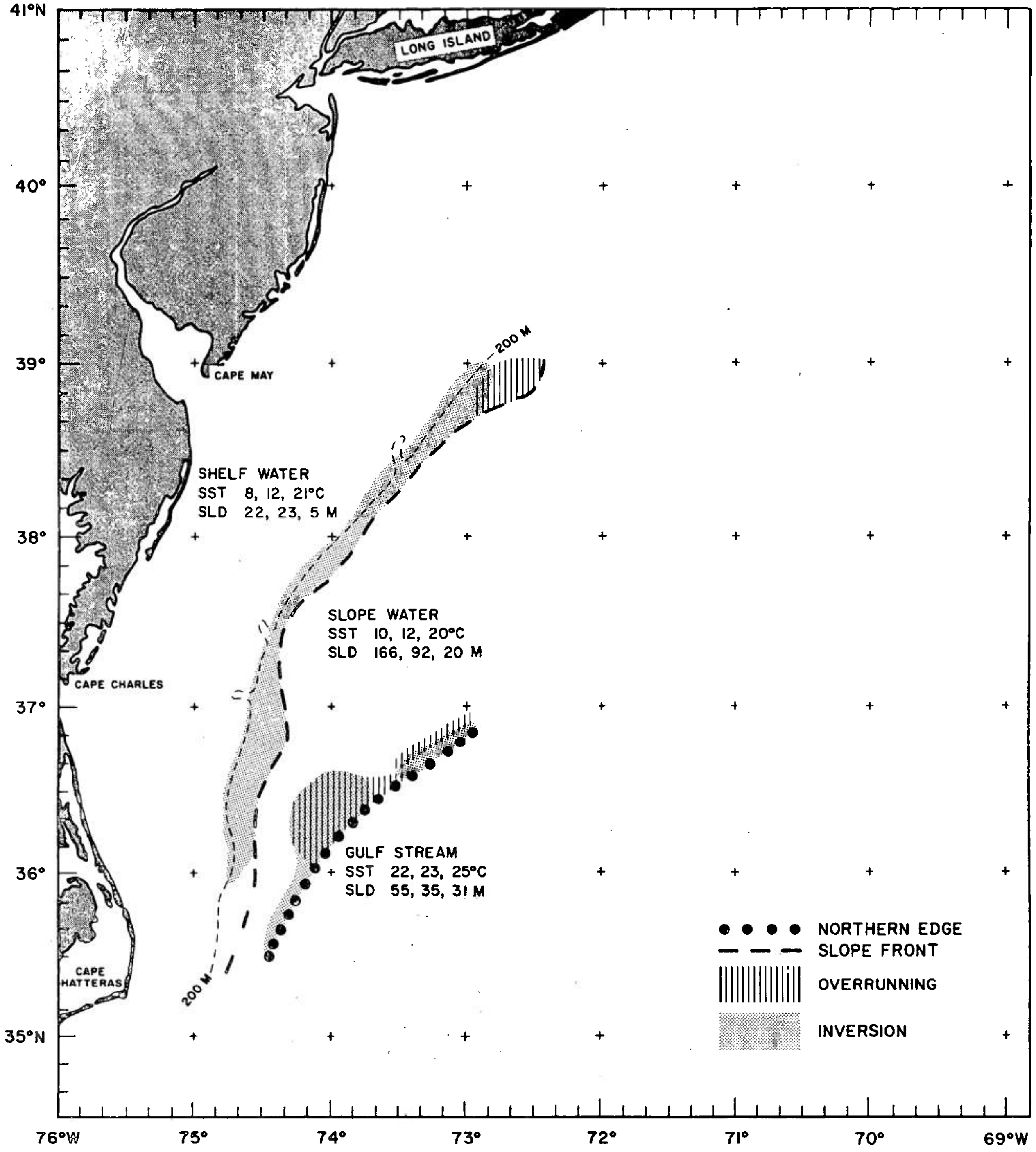

Figure 5 Spring thermal structure (April through June)

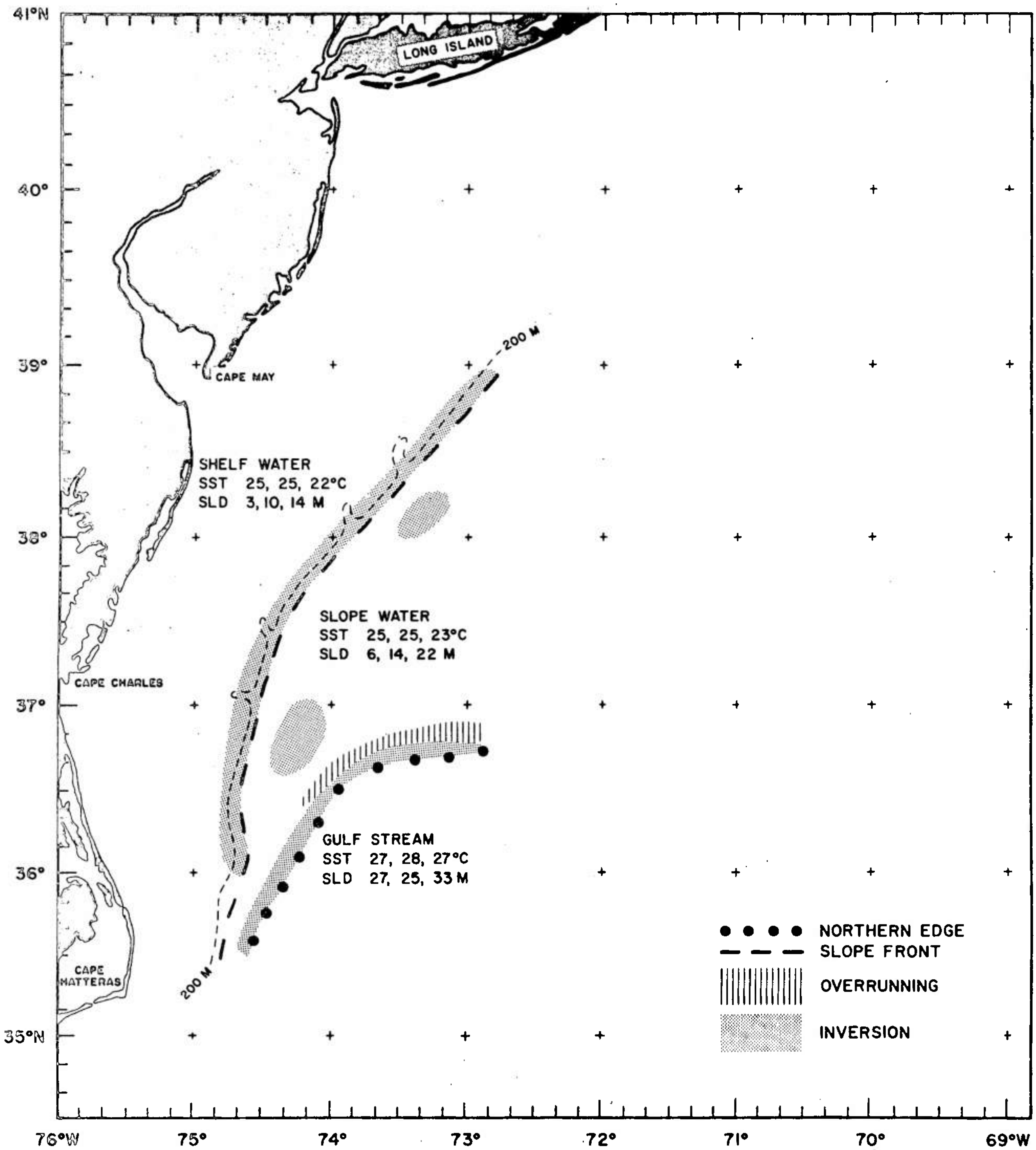

Figure 6 Summer thermal structure (July through September)

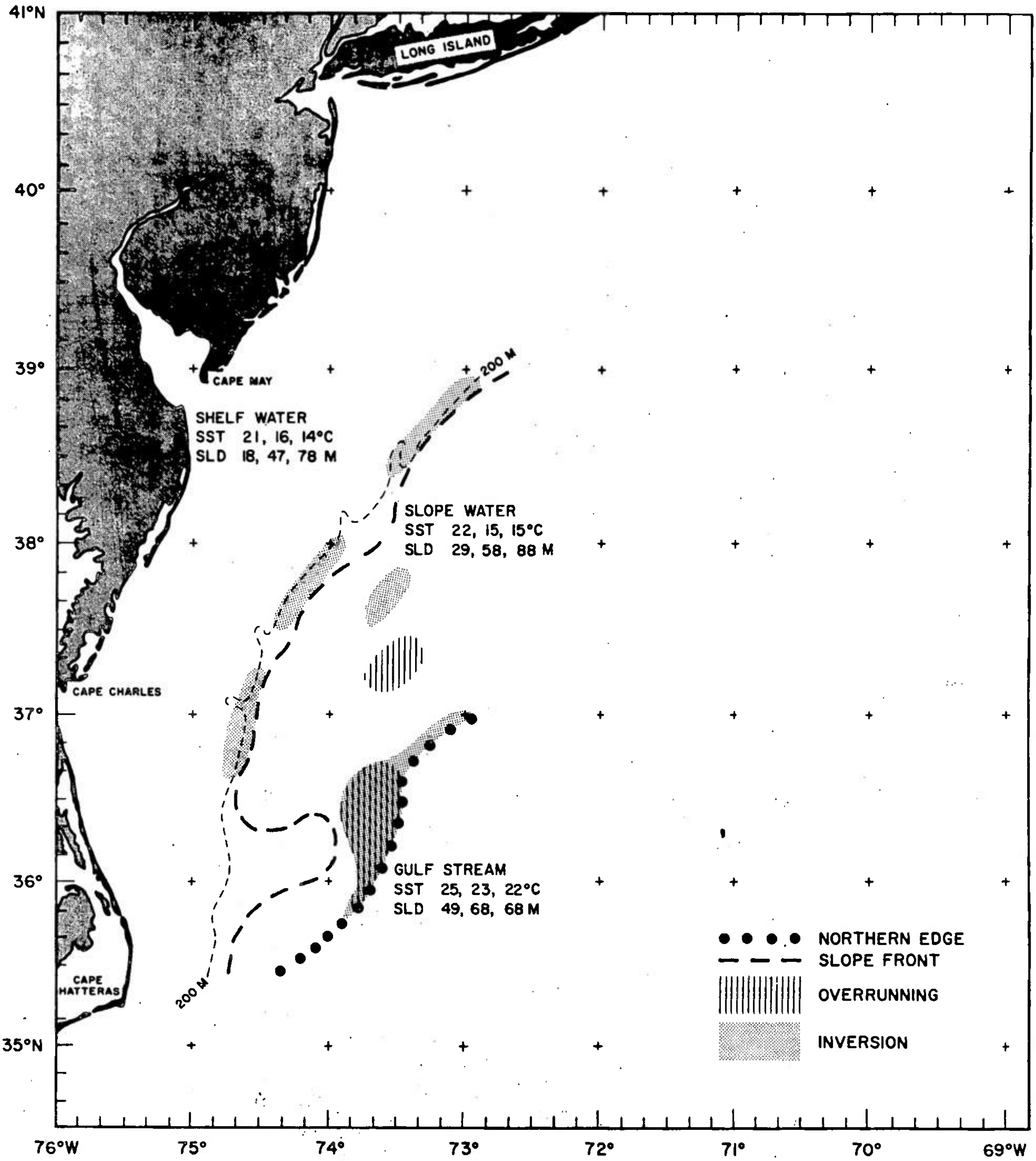

Figure 7 Autumn thermal structure (October through December)

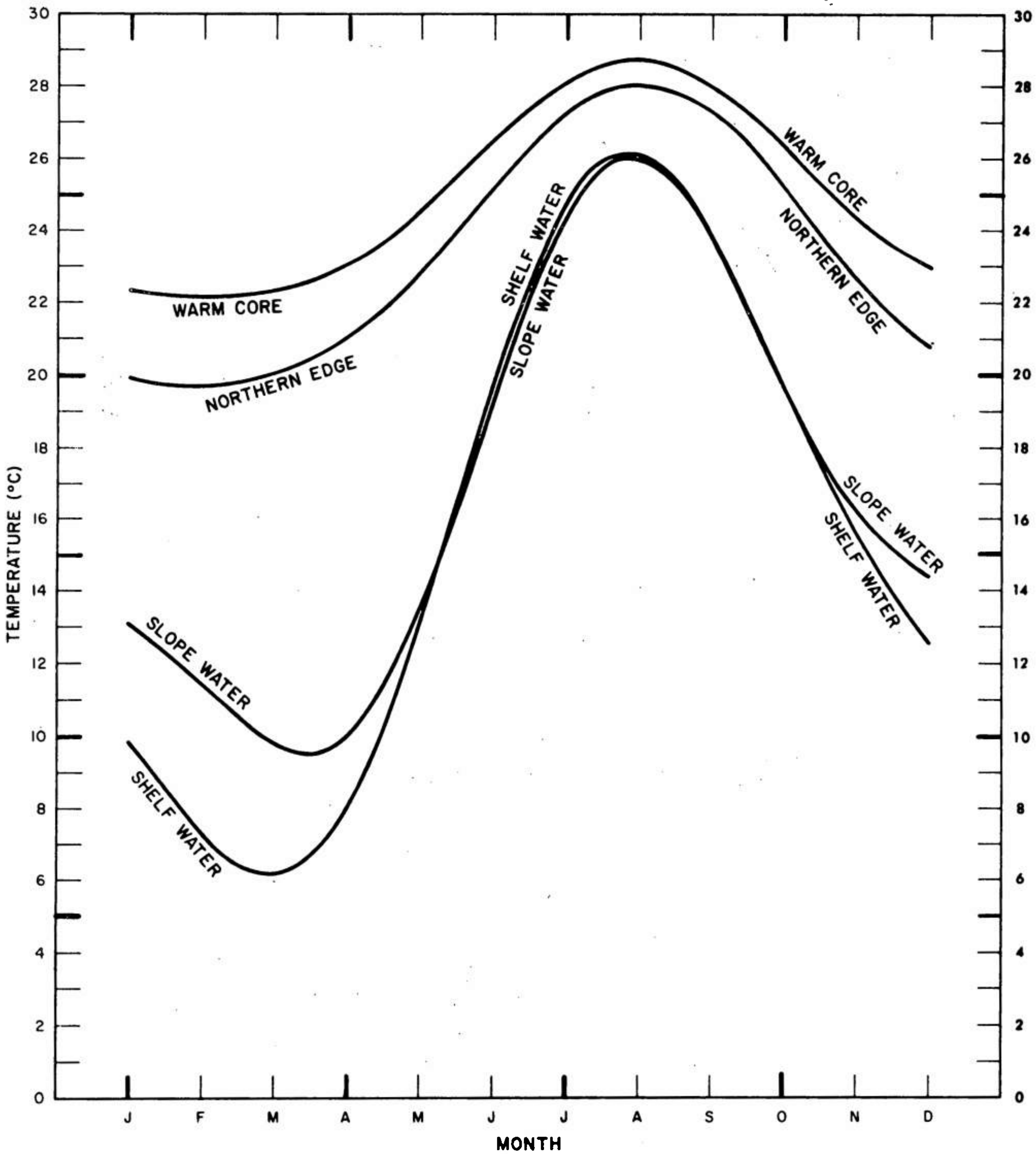

Figure 8 Mean monthly sea-surface temperature by water mass

Two temperature values are of particular interest in Gulf Stream thermal structure forecasting: (1) maximum SST of the northern edge and (2) maximum SST of the warm core. Figure 8 shows curves of mean monthly SST for the northern edge (as defined in section IV), and the warm core determined from harmonic analysis of airborne radiation thermometer (ART) data in the area between 70°W and 75°W. Maximum and minimum values of SST occur in August and February, respectively. The mean temperature difference between the warm side of the northern edge and the warm core varies from 0.7°C in August to 2.4°C in February.

Bathythermograms typical of Gulf Stream Water during each season are shown in figure 9. The winter trace shows relatively low SST (21.2°C) and deep sonic layer (120 m). Warming in spring is reflected by increased SST (24°C) and decreased SLD (38 m). This trend continues into summer with SST and SLD of 27.6°C and 21 m, respectively. Cooling and subsequent overturning of surface water result in decreased SST and increased SLD to 23.7°C and 43 m, respectively. Annual variation of SLD in Gulf Stream Water is less than in adjacent water masses. In summer, when minimum SLD occurs in the Gulf Stream, it is slightly deeper (10 m) than in Slope Water. In winter, when maximum SLD occurs in the Gulf Stream, it may be as much as 140 m less than in Slope Water. Layer depth tends to be greatest in the warm core of the Gulf Stream and least near the edges. Useful sound channels* generally are not associated with the Gulf Stream core but may occur near the northern and southern edges.

Two criteria can be used to distinguish Gulf Stream Water from Slope Water: (1) temperature at the 200-meter level is 15°C or greater compared to values below 15°C at this depth in Slope Water and (2) surface salinity is 36.0 $\pm$ 0.2 $^{o}/oo$ compared to less than 35.8 $^{o}/oo$ in Slope Water.

B. Slope Water

Slope Water lies in the triangular area between the northern edge of the Gulf Stream and the Continental Shelf. Surface temperature and salinity of Slope Water generally fall between those of Shelf Water and Gulf Stream and are thus indicative of considerable mixing between North Atlantic Central Water and coastal water.

The smoothed mean monthly SST curve for Slope Water and its relationship to adjacent water masses are also shown in figure 8. Maximum and minimum SST occur in Slope Water during August and March-April, respectively. The late minimum SST is due to the lag between the date of coldest air temperatures and the time surface heating is effective in raising the SST. Gulf Stream Water does not exhibit this lag owing

*Relative sound channel strength is defined in the appendix.

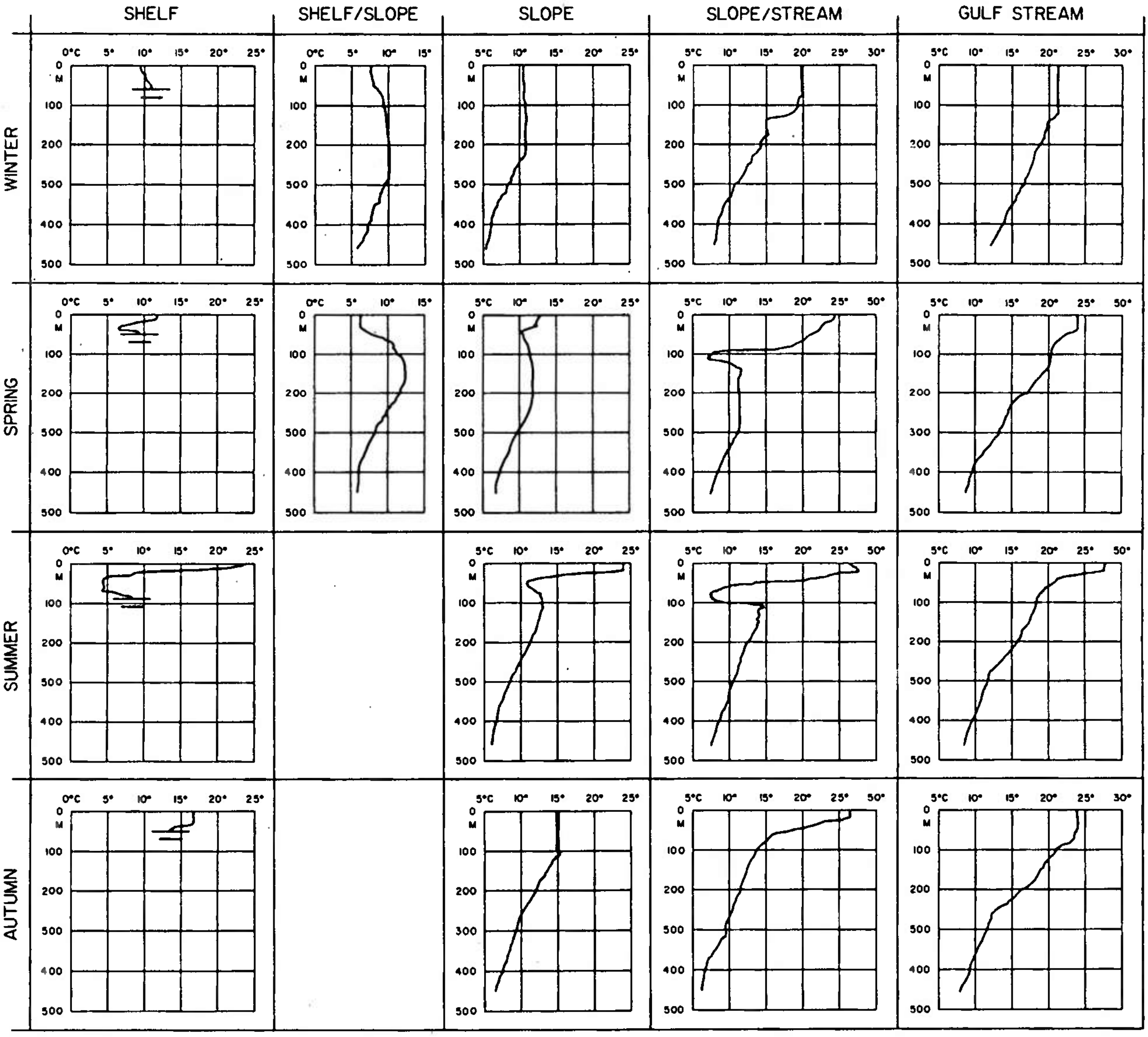

Figure 9 Seasonal bathythermogram characteristics by water mass (°C, M)

to the continual influx of tropical water. Note that the annual range of SST in Slope Water (16°C) is greater than that of the Gulf Stream (7°C) and less than that of Shelf Water (18°C), thus making tentative water mass identification possible from surface temperature measurements during all seasons except summer. Variability of Slope Water SST, as shown in figure 10, is greatest in spring and least in summer and autumn. Mean monthly SST and 95-percent confidence limits are shown in this figure. Mean annual temperature at 400 meters was computed to be 6.8° $\pm$ 0.6°C, indicating that water at this depth is little affected by seasonal change.

Layer depth in Slope Water is generally greatest in winter and least in summer as shown in figure 11. The variability is greatest in winter and early spring and least in summer. A rapid increase of layer depth in autumn coincides with maximum surface cooling. Deepening of SLD continues into late winter when layer depths occasionally exceed 300 meters. Slope Water SLD is considerably deeper during winter than SLD in adjacent water masses. The SLD shoals rapidly in spring when increased solar radiation causes rapid heating at the surface. During summer Slope Water SLD (6 m) is comparable to SLD in Shelf Water and shallower than SLD in Gulf Stream Water (25 m). Zero layer depth occurred most frequently during July (65 percent) and least frequently from early November until March (less than 5 percent) as shown in figure 12.

Sound channels occur more frequently in Slope Water than in adjacent water masses. Highest frequency occurs near the slope front from spring through midautumn and at the northern edge throughout the year. See figure 9 for examples of sound channels. Large subsurface cold cells may break off from an inversion impinging upon the Continental Slope and drift seaward into Slope Water. During winter and early spring, when a near-isothermal layer may occur to 300 meters, warm water overrunning from the Gulf Stream or surface heating subsequent to cold overrunning by Shelf Water may create strong depressed sound channels.

The seasonal thermocline is strongest during midsummer, when solar radiation is maximal and surface winds are minimal. Overturning destroys the seasonal thermocline by late autumn, and the seasonal thermocline will not reappear until solar radiation in spring is sufficient to offset heat lost to the atmosphere by long-wave radiation. Positive temperature gradients (ascendants) may occur, particularly during winter, where cold Shelf Water overruns Slope Water. This is frequently observed northeast of Cape Hatteras, where Shelf Water is entrained by the Gulf Stream.

Characteristic Slope Water bathythermograms are shown in figure 9. Cold (SST:10.3°C), well-mixed water (SLD:220 m) typical of the winter shows no seasonal thermocline or sound channel. Reestablishment of the seasonal thermocline in spring is a direct result of increased solar heating. The rise in SST (to 12.8°C) is sufficient to cause zero layer

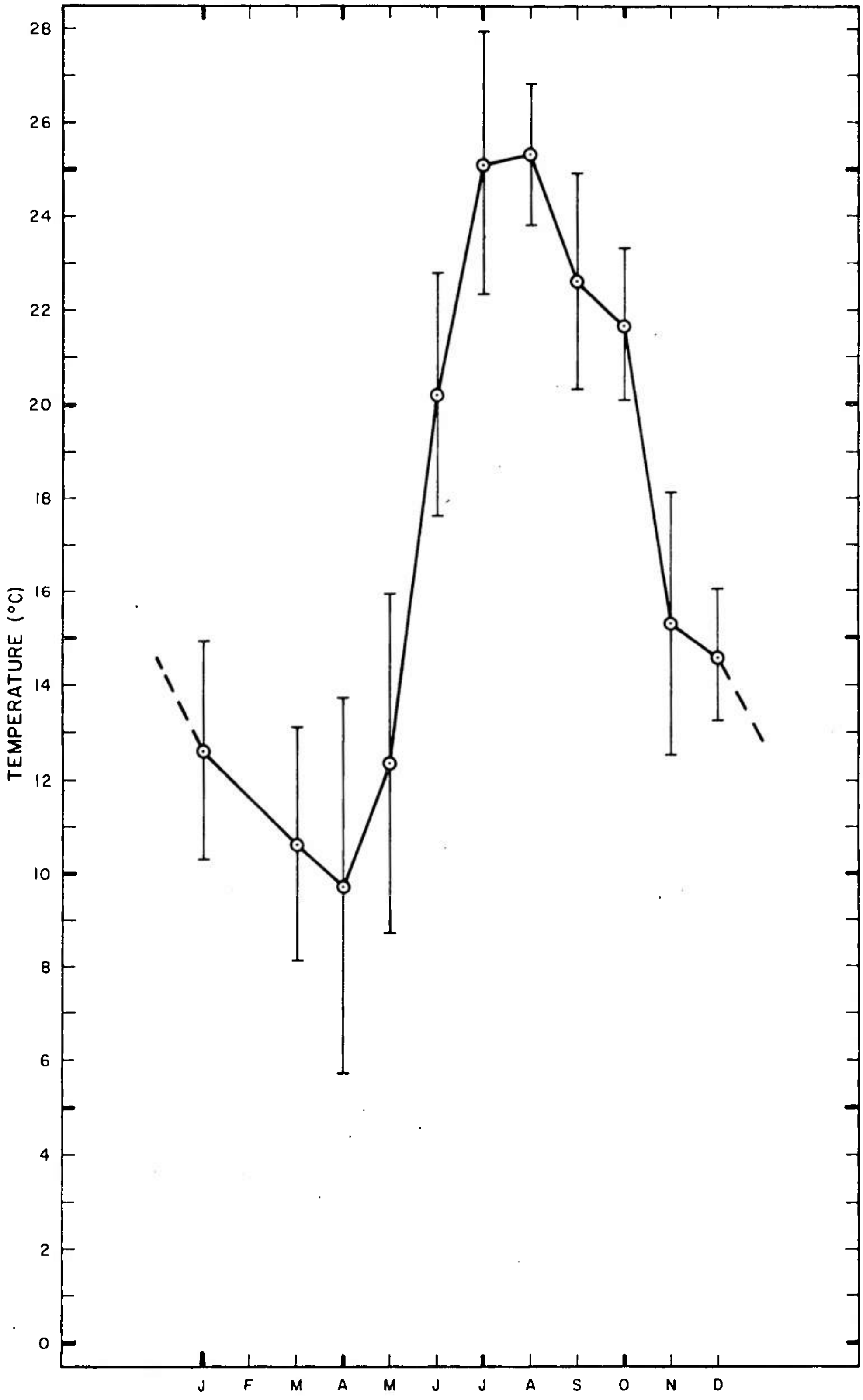

Figure 10 Variability of sea surface temperature, Slope Water

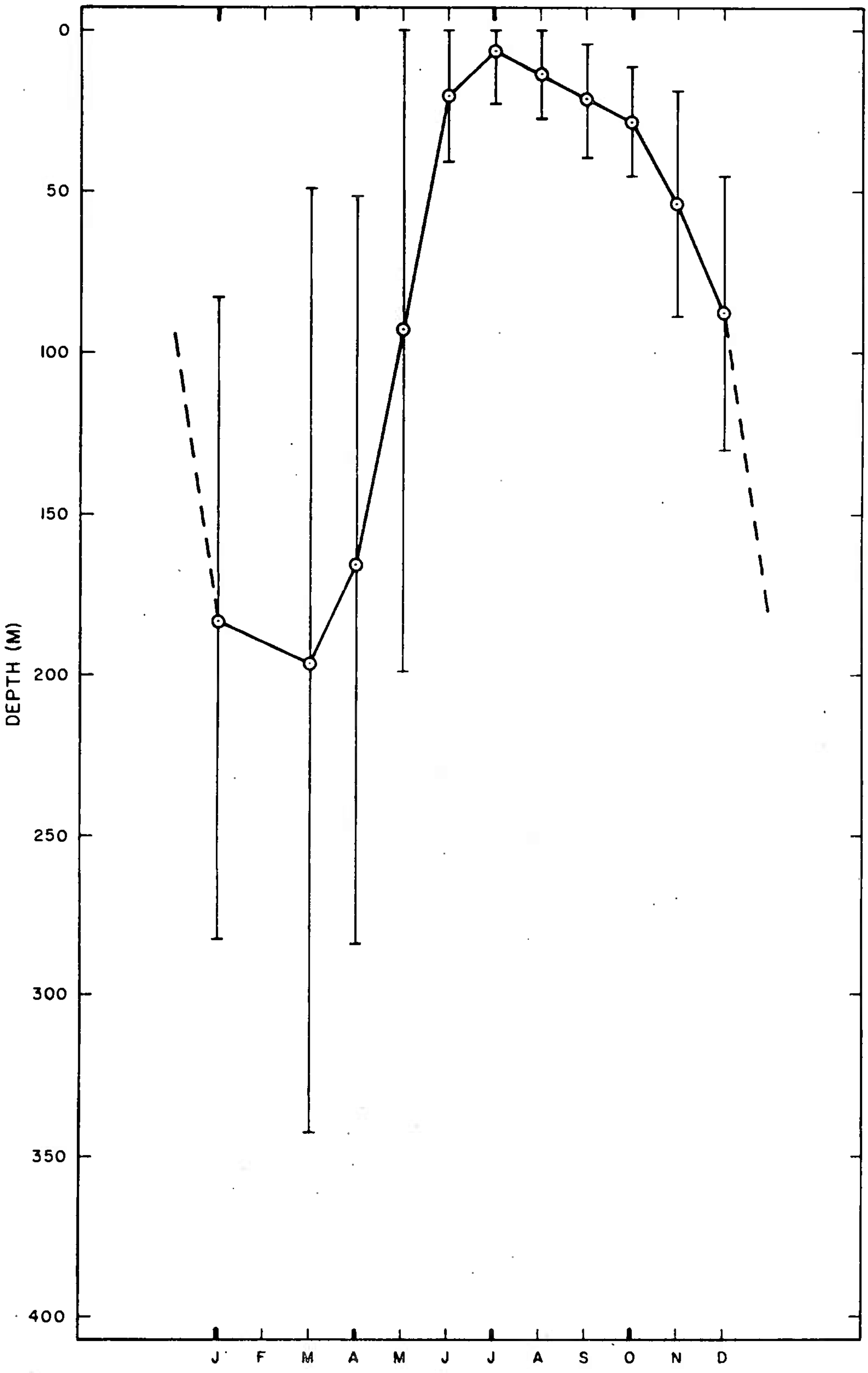

Figure 11 Variability of sonic layer depth, Slope Water

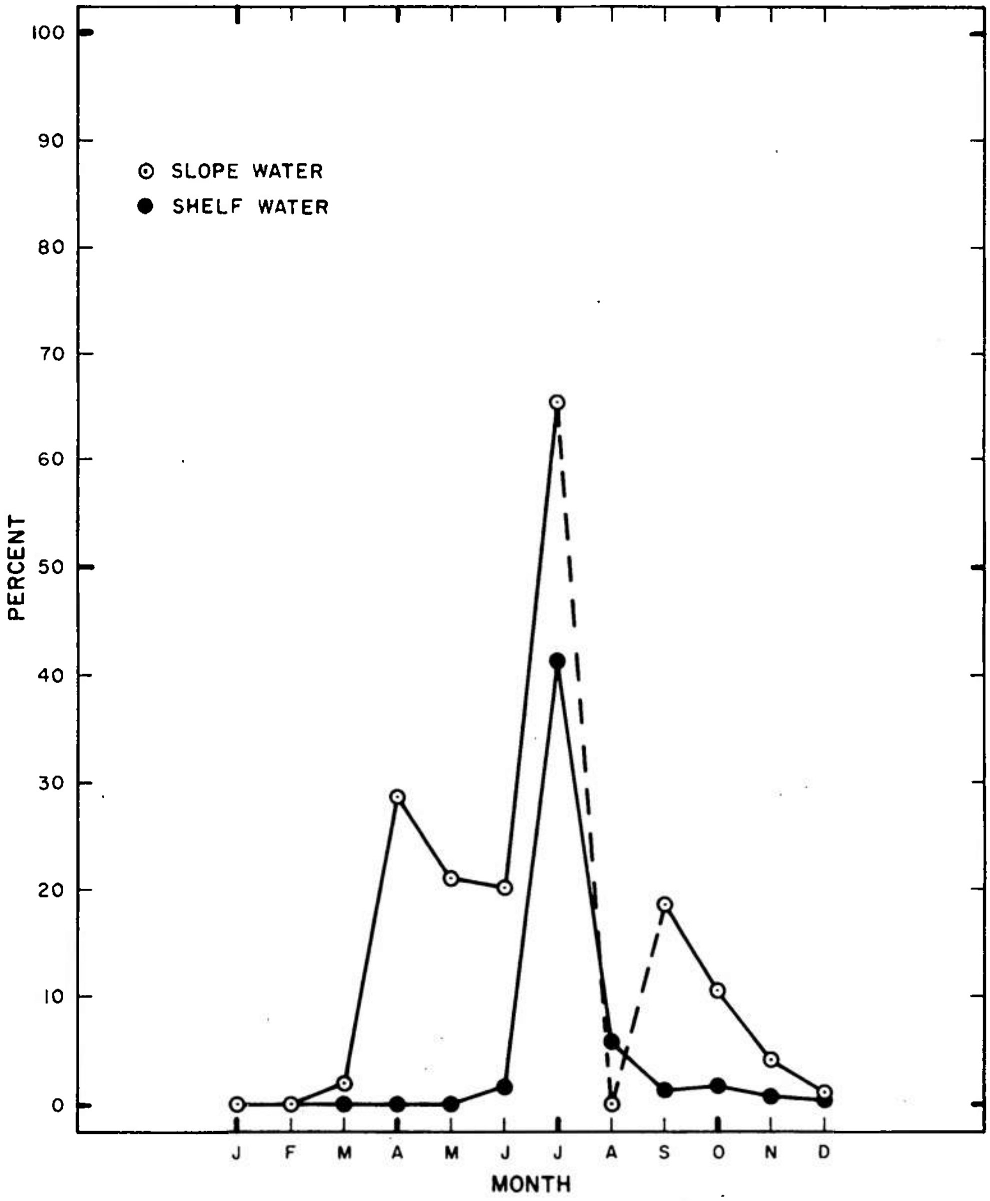

Figure 12 Frequency of zero sonic layer depth, Shelf Water and Slope Water

depth despite presence of a thick subsurface layer of near 12°C water. The combination of the near-isothermal layer and a cold inversion (10°C) at the base of the near-surface thermocline causes a strong sound channel. The summer observations reflect increasing SST (to 24°C) and thermocline strength in response to continued heating. The sound channel remains strong despite near-destruction of the underlying isothermal layer. Cooling and increased winds in autumn cause destruction of the seasonal thermocline and underlying sound channel as shown by decreasing SST (to 15°C) and SLD deepening (to 105 m). The small temperature maximum near 100 m is indicative of incomplete overturning.

C. Shelf Water

Water overlying the Continental Shelf,termed Shelf Water, is basically northern coastal water advected into the Virginia Capes area, where it is modified by local coastal water and the atmosphere. Data used to compute statistical indices describing Shelf Water were collected in the zone bounded by the 30-m and 200-m isobaths. The inshore boundary was selected to minimize the effects of rapidly fluctuating influx of river water from the Middle Atlantic States, and the offshore boundary was chosen because of its proximity to the Slope Front.

The annual temperature range of SST in Shelf Water, as shown from mean monthly values and the smoothed curve of SST in figure 8, is greater in Shelf Water than the range in either the Gulf Stream or Slope Water. Maximum and minimum SST occur in August and February-March, respectively. Greatest variability in SST occurs during winter and spring as shown by figure 13. The large temperature ranges (annual and monthly) are due to relatively rapid energy exchange between air masses and relatively shallow water.

A previous study (Bigelow and Sears, 1935) of salinity distribution over the Continental Shelf between Cape Cod and Cape Hatteras shows an increase from 32-33.5 $^{o}/oo$ in midshelf to 34-35 $^{o}/oo$ near the shelfbreak with little salinity variation lengthwise on the shelf; isohalines tend to be parallel to the coast with values increasing seaward. A lag of several months occurs between periods of high precipitation on the continent and introduction of the runoff into coastal waters. Several more months may be required before the effect of runoff reaches the outer regions of the Continental Shelf. Thus, it is not surprising that minimum salinity on the outer shelf occurs in late winter, nearly a year after the period of maximum rainfall on the continent.

Minimum SLD (less than 5 m) occurs in June and July, as shown by the mean value and 95-percent confidence limits in figure 14. Mean values, and thus variability, were not computed for January through April when SLD occurred at the bottom in 50 or more percent of the observations. Maximum SLD occurs in February and March,when 95 percent of the observations showed SLD at the bottom. Figure 15 indicates percent of time SLD is at the bottom for Shelf Water.

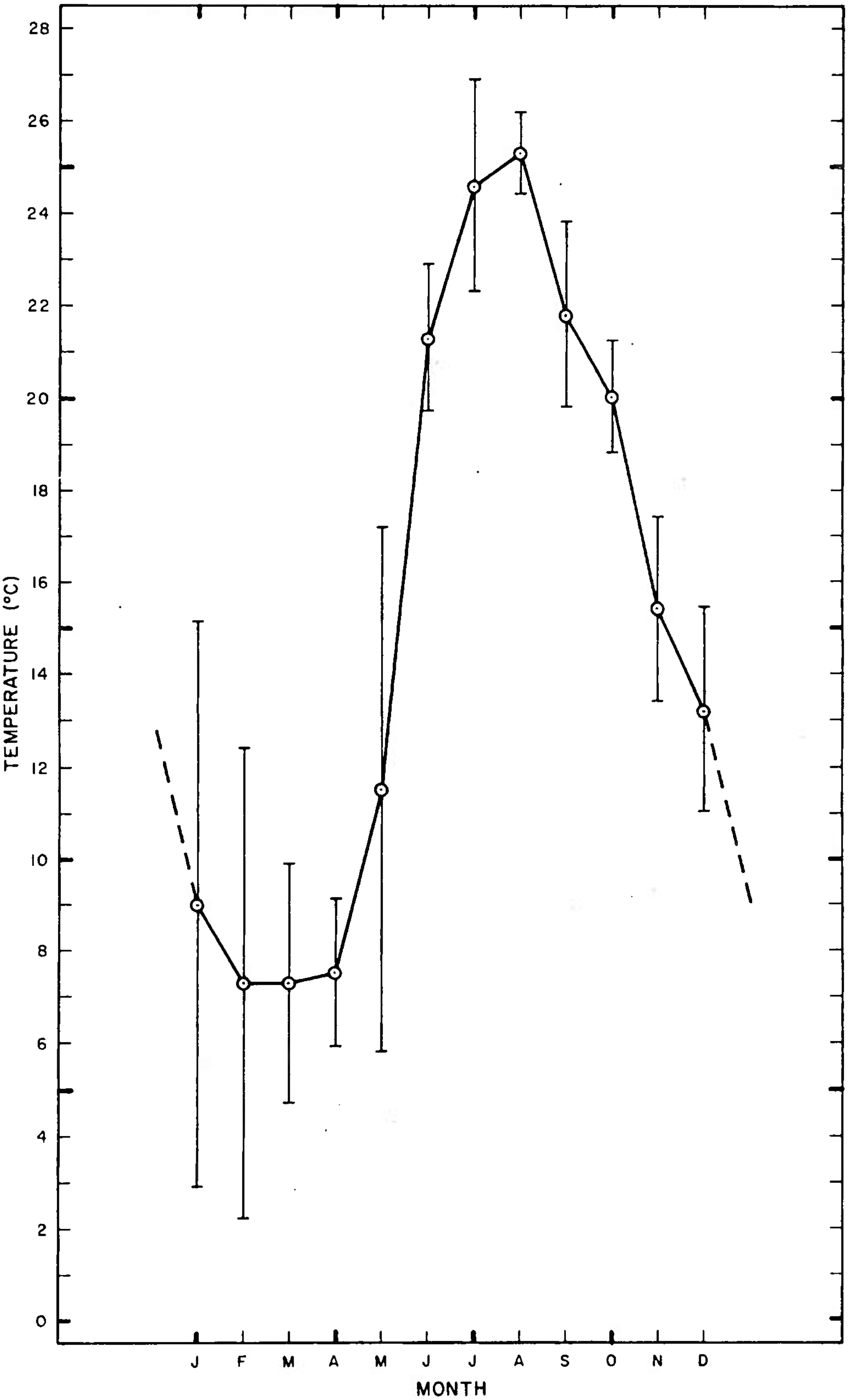

Figure 13 Variablity of sea surface temperature, Shelf Water

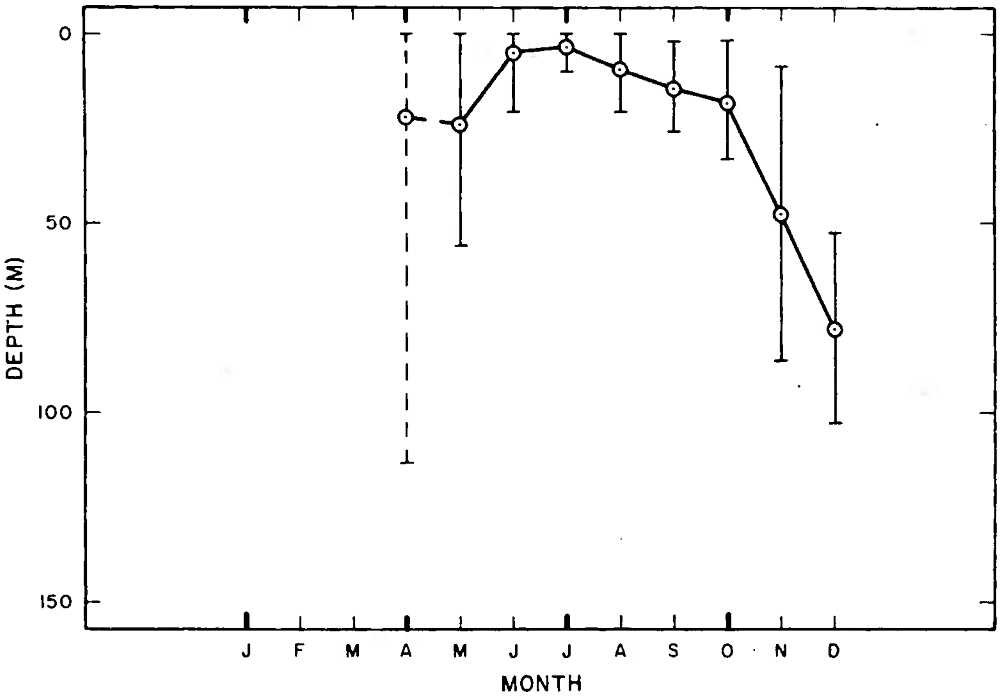

Figure 14 Variability of sonic layer depth, Shelf Water

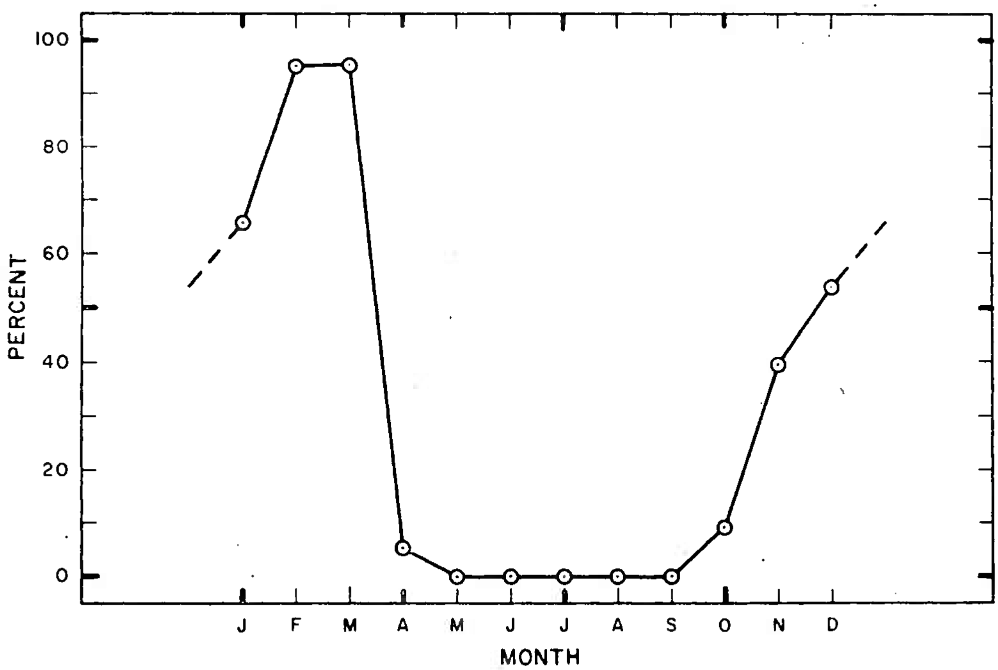

Figure 15 Frequency of sonic layer depth occurring at bottom, Shelf Water

Useful sound channels are observed only near the shelf break, where the water is sufficiently deep for the formation of well-defined temperature inversions between April and October.

A strong thermocline occurs in summer and is strongest where warm surface water is underlain by a temperature inversion. Destruction of the seasonal thermocline is completed by November, and strong positive gradients may occur in late winter when surface cooling is greatest. The thermocline reappears in midspring when solar radiation increases. Thermal traces characteristic of Shelf Water during each season are shown in figure 9.

Table 1 summarizes the near-surface thermal characteristics of the major water masses in the VACAPES area. Where sufficient data are available the mean and 95-percent confidence limits are shown; otherwise only the mean values are presented. These variables, when used in conjunction with temperature values at depth, are sufficient to identify the water masses. Typical temperatures at the 200-meter level are: Slope Water, 9.0 to 14.9°C; Gulf Stream Water 15.0°C and above. Gulf Stream Water may be distinguished from Sargasso Water to the east in that the former is less than 15.0°C at the 400-meter level. Shelf Water is readily identified by water depth less than 200 m.

In summary, there are three basic water masses in the VACAPES area: Shelf, Slope, and Gulf Stream. Each water mass is characterized by different thermal profiles so that one can identify fairly easily the water mass in which the ship is operating. If deep layer depths, sharp horizontal or vertical gradients, sound channels or some other specific thermal parameter are desired, the information presented in this section can be used to determine where and when one would be most likely to find the desired conditions.

IV. OCEAN FRONTS

The boundaries of adjacent water masses are marked by oceanic fronts somewhat similar to meteorological fronts. These fronts exhibit conspicuous horizontal temperature gradients, they move under the pressure of denser water intrusions, and one water mass overrides another. Thermal characteristics change rapidly in fronts, and, consequently, the performance of sensors and weapons may exhibit anomalous behavior in these regions.

Two major oceanic fronts occur in the VACAPES area: the northern edge of the Gulf Stream and the slope front. A third front, the southern edge of the Gulf Stream, lies to the east of the VACAPES area. This front is weaker than either the northern edge or the slope front.

A. Northern Edge

The northern edge of the Gulf Stream, separating Gulf Stream Water from Slope Water, is an area of intense mixing between two water

TABLE 1 WATER MASS THERMAL CHARACTERISTICS

Season	Month	Shelf Water SST (°C)	Shelf Water SLD(M)	Slope Water SST(°C)	Slope Water SLD(M)	Gulf Stream Water SST(°C)	Gulf Stream Water SLD (M)
Winter	J	9.0±3.0	BOT	12.6±1.2	183±50	21.1	78
	F	7.3±2.6	BOT	11.4	203	20.8	59
	M	7.3±1.3	BOT	10.6±1.3	196±74	20.8	55

Remarks: A. Shelf Water considerably colder than Slope Water at all depths
B. Shelf Water mixed to bottom

Season	Month	Shelf Water SST (°C)	Shelf Water SLD(M)	Slope Water SST(°C)	Slope Water SLD(M)	Gulf Stream Water SST(°C)	Gulf Stream Water SLD (M)
Spring	A	7.5±0.8	22	9.7±2.0	166±57	21.5	55
	M	11.5±2.8	23±17	12.3±1.8	92±53	23.2	35
	J	21.3±0.8	5±8	20.2±1.2	20±10	25.4	31

Remarks: A. Maximum heating in late spring causes decreasing SLD
B. Strong sound channels occur in Slope Water
C. SLD in Gulf Stream Water deeper than in Slope Water and Shelf Water by June

Season	Month	Shelf Water SST (°C)	Shelf Water SLD(M)	Slope Water SST(°C)	Slope Water SLD(M)	Gulf Stream Water SST(°C)	Gulf Stream Water SLD (M)
Summer	J	24.6±1.1	3±4	25.1±1.4	6±5	27.2	27
	A	25.3±0.5	10±6	25.3±0.7	14±7	27.7	25
	S	21.8±1.0	14±6	23.2±1.0	22±9	26.6	33

Remarks: A. SST in Shelf Water may be greater than in Slope Water
B. Isolated sound channels occur in Slope Water
C. Deepest SLD occurs in Stream Water

Season	Month	Shelf Water SST (°C)	Shelf Water SLD(M)	Slope Water SST(°C)	Slope Water SLD(M)	Gulf Stream Water SST(°C)	Gulf Stream Water SLD (M)
Autumn	O	20.6±0.6	18±9	21.7±0.8	29±9	24.7	49
	N	16.4±1.0	47±20	15.3±1.4	58±20	22.9	68
	D	14.3±1.1	78±13	14.6±0.7	88±22	21.7	68

Remarks: A. SST in Shelf Water may be greater than in Slope Water
B. Maximum cooling in late autumn causes deepening SLD
C. SLD in Stream Water deeper than in Shelf Water and Slope Water in October and November

masses of different thermohaline characteristics. The scale of mixing varies from large wave-like perturbations in the northern edge (meanders) greater than 100 km in length to small features undetectable by standard survey techniques. Spatial variation in the northern edge is common, as shown by the mean position and 95-percent confidence limits of the position of the northern edge using infrared radiation data collected between 1966 and 1969 (figure 16). Large spatial displacement probably results from sudden changes in Gulf Stream flow responding to a variable bottom and hydrodynamic forces. A discussion of Gulf Stream dynamics is beyond the scope of this guide; the subject has been treated in more detail in many theoretical reviews, e.g. Stommel (1966), Hansen (1970).

An example of large-scale displacement of the northern edge was observed during a 6-week period in the spring of 1970. The surface configuration of a large meander is shown by the 25° isotherm in figure 17. In this case the northern edge is well to the northwest of its normal position. Progression of the meander downstream is shown by figure 18, where the location of the 15°C isotherm at a depth of 200 m is plotted from airborne expendable bathythermographs. On 25 April 1972, the northern edge was well within the 95-percent limits shown in figure 16. A large meander had moved into the area previous to the second flight in the series (10/11 May), with the meander crest outside the 95-percent limits. The meander moved downstream at a speed of about 7.8 km/day during the 3-week period.

Smaller perturbations occur in the near-surface layer of the northern edge without affecting orientation of the northern edge at the 200-m level. Displacement of this scale (overrunning) frequently occurs northeast of Cape Hatteras, perhaps because of changes in bottom topography. An area of overrunning, defined by the bend in the 21°C isotherm, is shown in figure 19, where water of Gulf Stream origin overruns Slope Water for some 50 km northwest of the northern edge. Because of the unique properties caused by Gulf Stream overrunning of Slope Water, this mixture can be thought of as a new water type, although very often temporary. For identification it will be called Boundary Water.

Bathythermograms taken in the overrun area show (1) the 15°C isotherm at 200 m on 10 and 11 May is nearly coincidental with the 23°C isotherm at the surface; (2) thickness of the overrunning varies from near 200 m in the center of the feature to 50 m at the edge; (3) frequency of useful sound channels in Boundary Water is 83 percent compared to 68 percent in Slope Water, 31 percent in Shelf Water, and 0 percent in the Gulf Stream; and (4) SLD in Boundary Water (15 m) was greater than SLD in Shelf Water (8 m) and less than SLD in Slope Water and in the Gulf Stream (both 35 m). During the 5-day period of observation (12-16 May 1969) the area of overrunning increased (figure 20). Perturbations have also been observed as closed eddies or as distorted tongues.

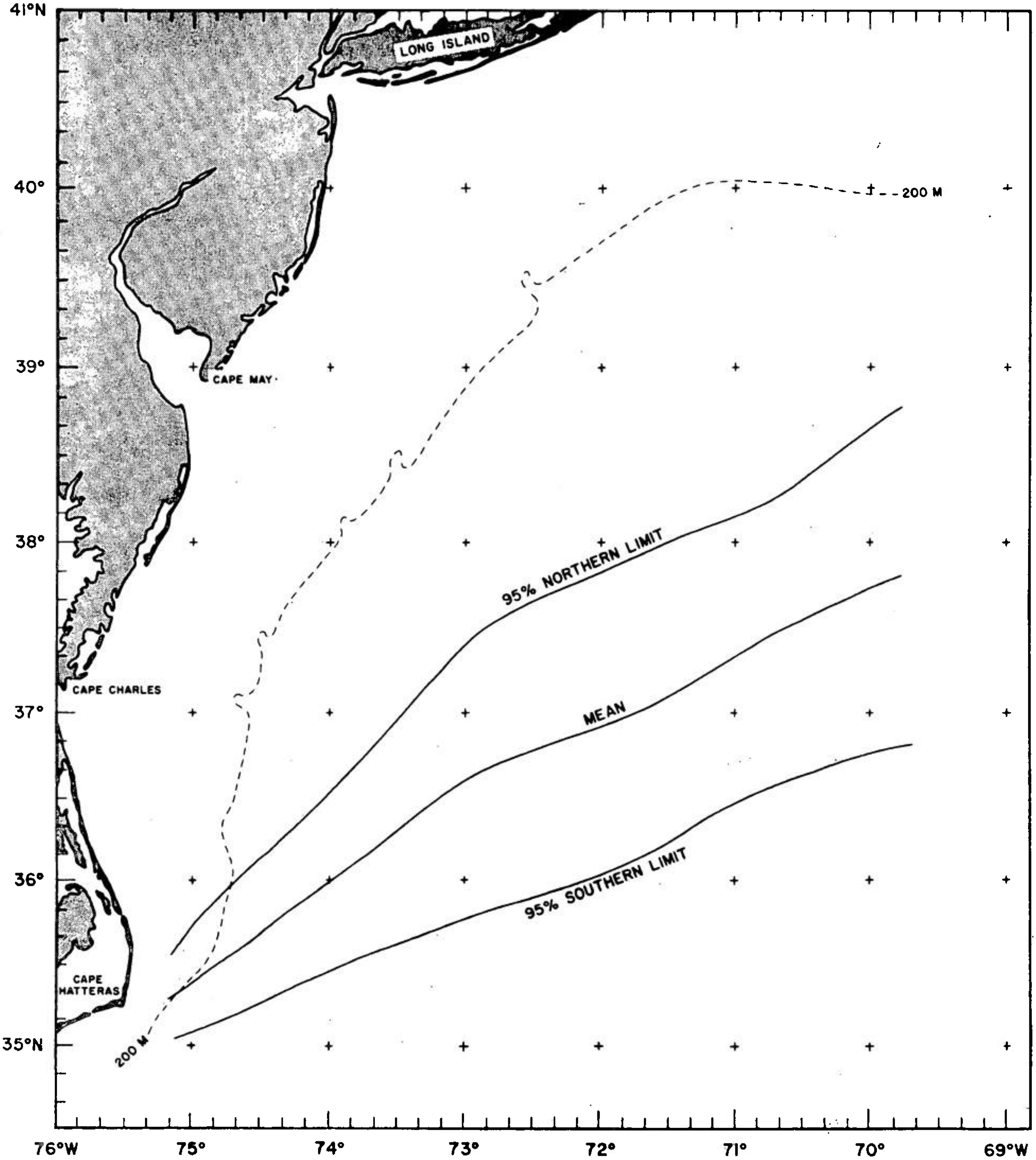

Figure 16 Mean position and variation of the northern edge (after Bratnick and Kerling)

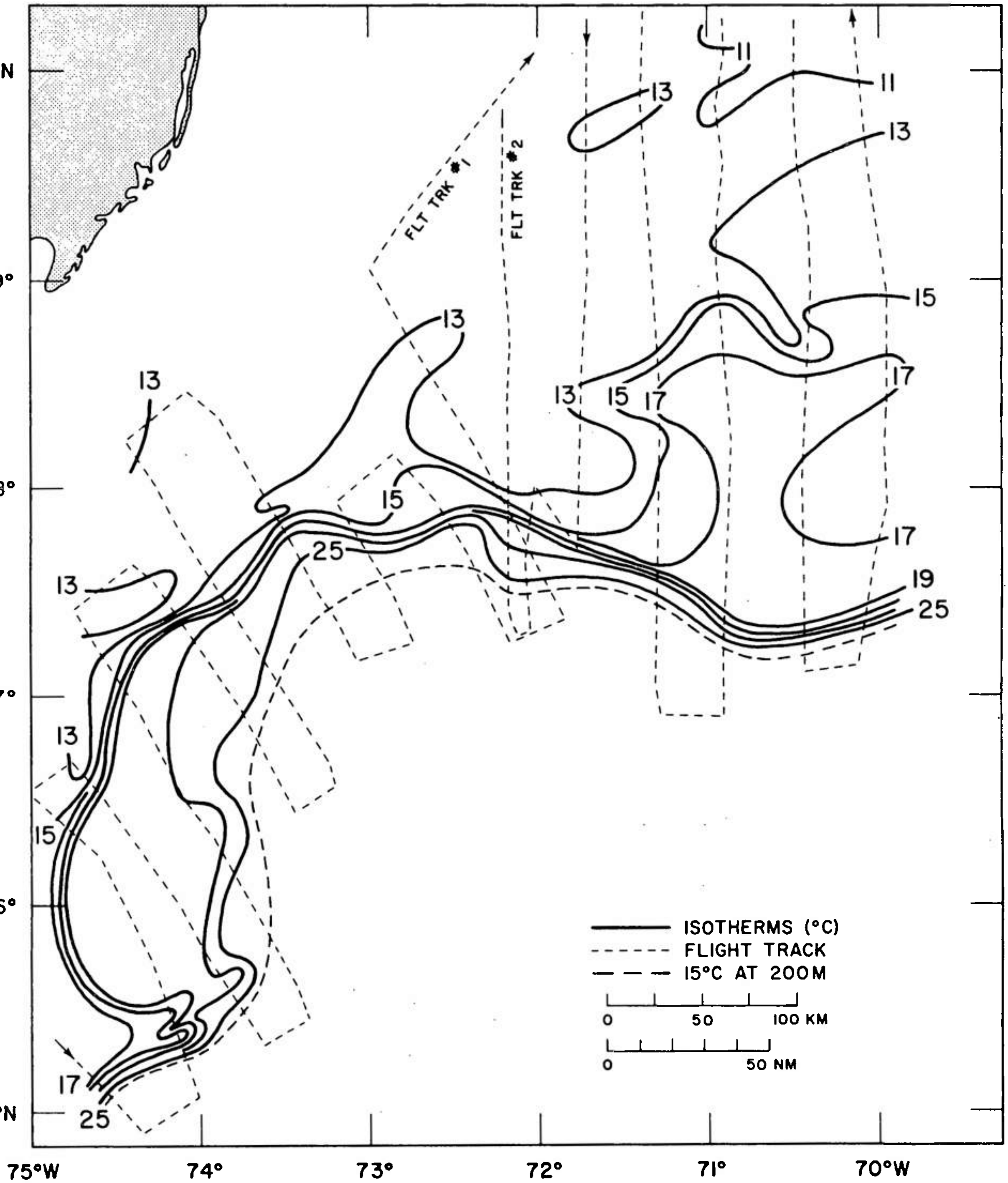

Figure 17 Gulf Stream meander, 10-11 May 1970

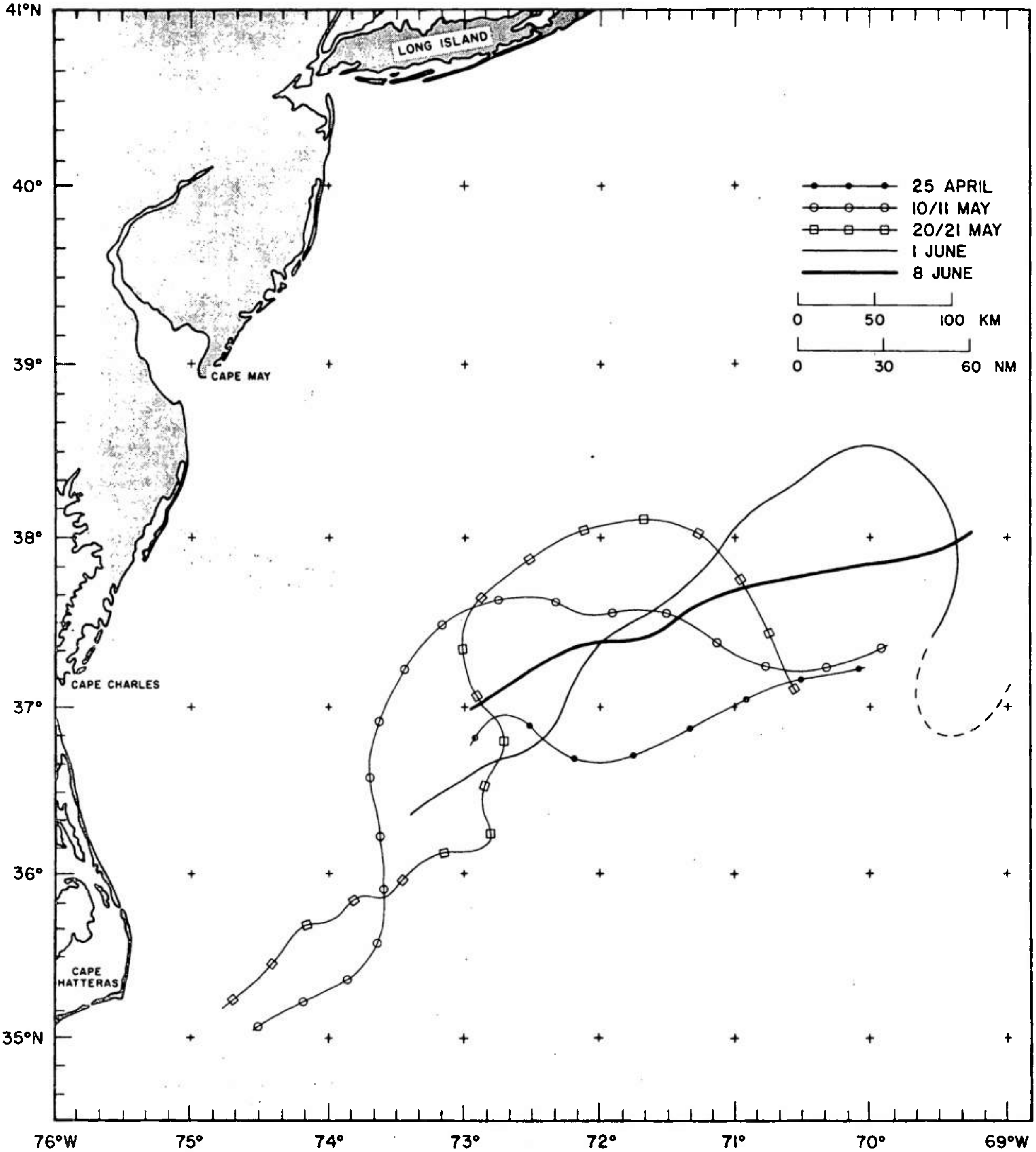

Figure 18 Progression of Gulf Stream meander, April—June 1970

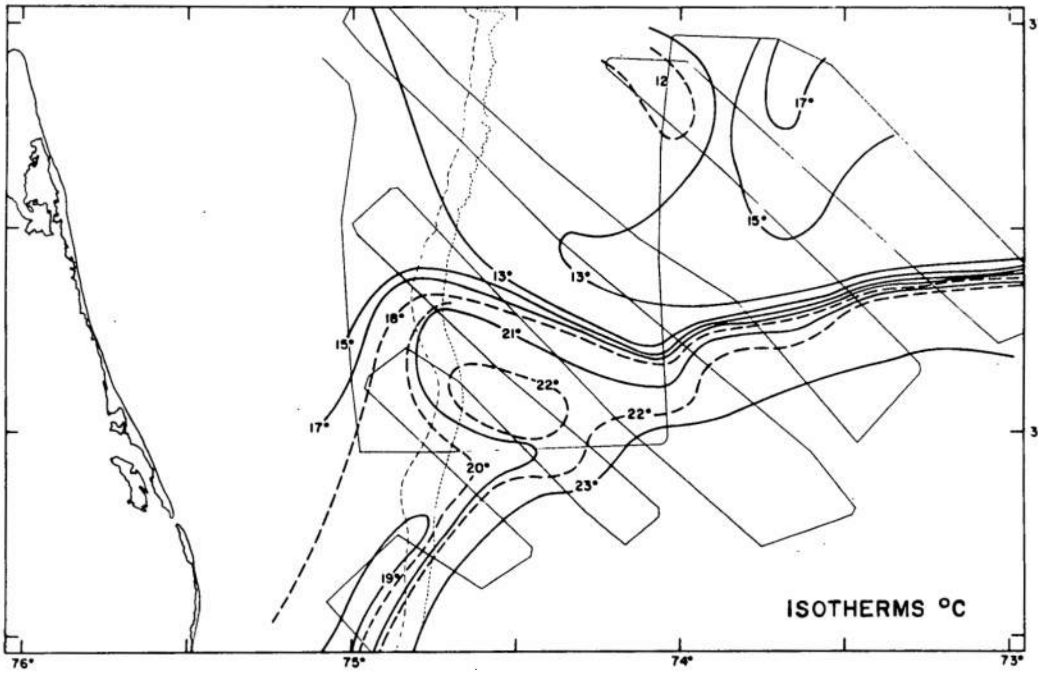

Figure 19 Gulf Stream Water overrunning Slope Water, 12 May 1969

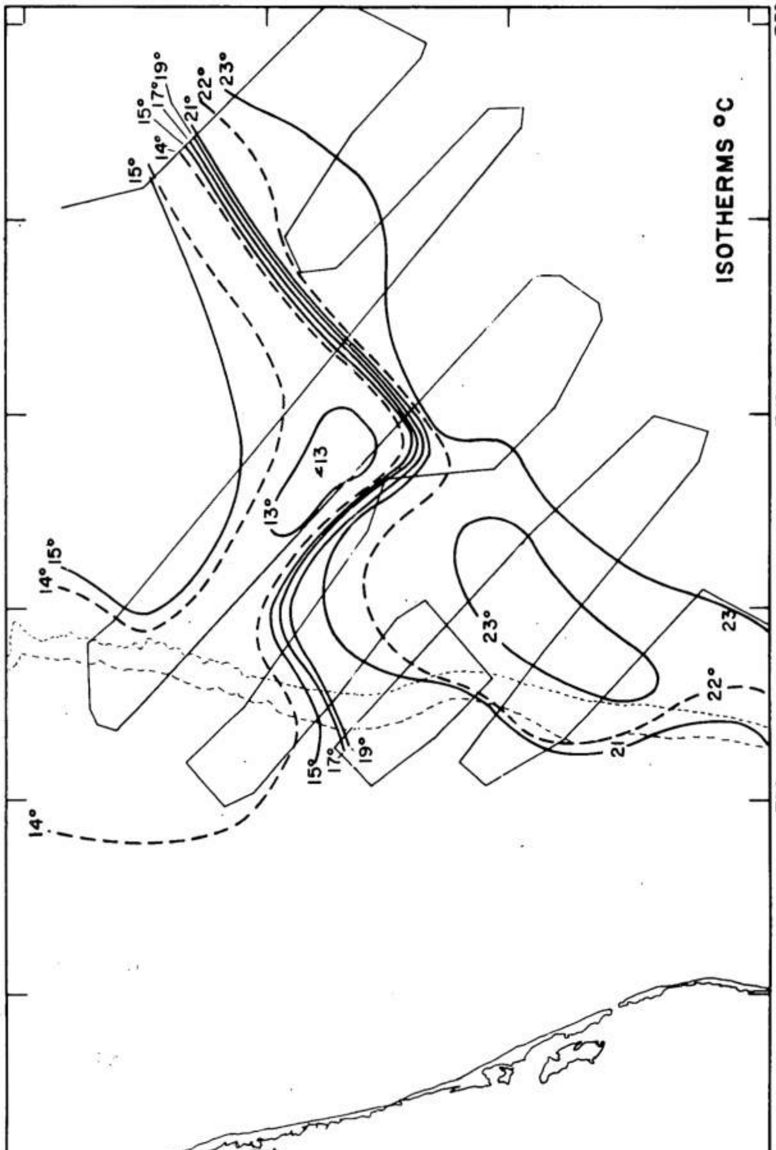

Figure 20 Gulf Stream overrunning Slope Water, 16 May 1969

A statistical investigation of the northern edge by Hansen and Maul (1970) provides considerable information of value to the thermal structure forecaster. The mean horizontal distance between the strongest horizontal temperature gradient at the surface and that at 200 m was found to be 14.5±11.8 km. This distance was less (11.3±8.1 km) near meander crests than near inflection points (14.2±9.7 km) or troughs (16.2±13.4 km). Little seasonal or geographical variation was noted. The northern edge at 200 meters was located to the right of the surface gradient (looking downstream) on 96 percent of all Gulf Stream transections. Exceptions were noted during severe atmospheric frontal passages.

The surface outcrop of the northern edge is frequently observed as a number of small thermal gradients rather than as a single strong gradient. An example of a so-called multiple gradient (figure 21) shows a 2-step increase from about 10°C in Slope Water to 23°C at the warm side of the northern edge. Airborne radiation thermometer (ART) observations of the northern edge between 70°W and 75°W show a frequency range of multiple gradients from 25 percent in summer to 54 percent in winter. Annual mean occurrence of multiple gradients was 46 percent. Because of the high frequency of such gradients, statistical investigation of the thermal gradient across the northern edge may be misleading. Where single gradients were observed in the study area, the strength of the gradient varied from near 3°C/km to less than 1°C/km.

Southerly moving Shelf Water is frequently entrained by the Gulf Stream system where it becomes a cold, relatively fresh filament adjacent to the northern edge. During 58 percent of a series of ART flights, a well-defined cold tongue was observed to extend seaward from the Continental Shelf toward the Gulf Stream (Fisher and Gotthardt, 1970). The tongue was absent on only 16 percent of the flights.

Cold filaments adjacent to the northern edge have been reported on numerous occasions. Church (1937) described a cold zone 1.8 to 3.7 km in width with SST about 1°C less than that in adjacent Slope Water. The cold filament is often discontinuous and occupies only a small part of the Gulf Stream's length.

Entrainment can be seen in figures 19 and 20 in which 13-14°C water stretches eastward from the shelf break parallel to the northern edge. Minimum SST and surface salinity in the entrainment were 11.2°C and 33.2 ‰, respectively. A plot of surface salinity (figure 22) shows excellent agreement with the temperature pattern in that the 33.5 ‰ isohaline is nearly coincident with the 13°C isotherm. The vertical extent of the entrainment and its relationship to adjacent water masses are shown in an expendable BT section across the same entrainment (figure 23). Location of the section is shown by the line AA' on figure 22. In this example the entrainment was observed to be about 14 kilometers wide and 40 meters thick. The width decreased to 2 kilometers farther downstream.

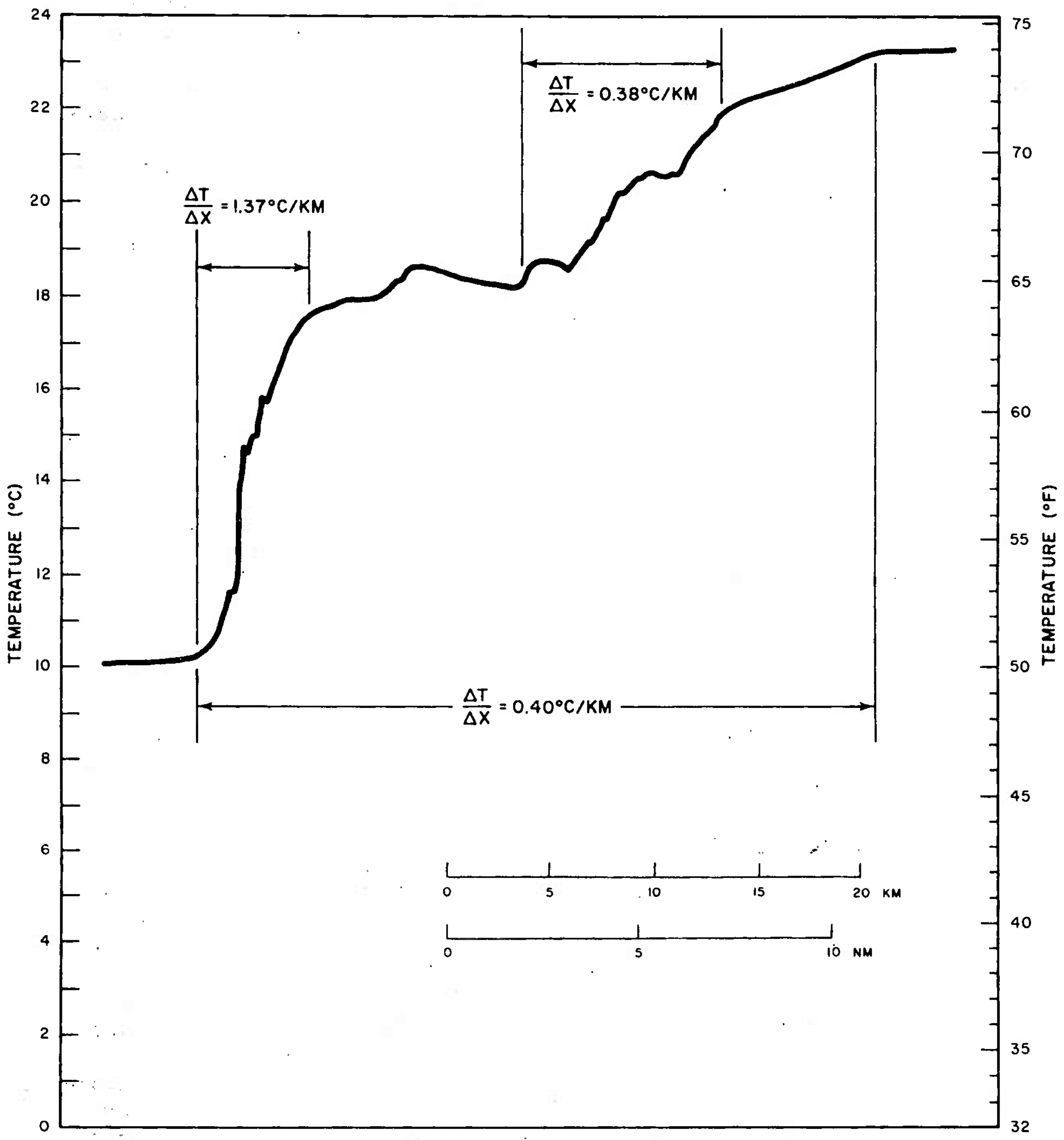

Figure 21 Multiple surface gradient, northern edge

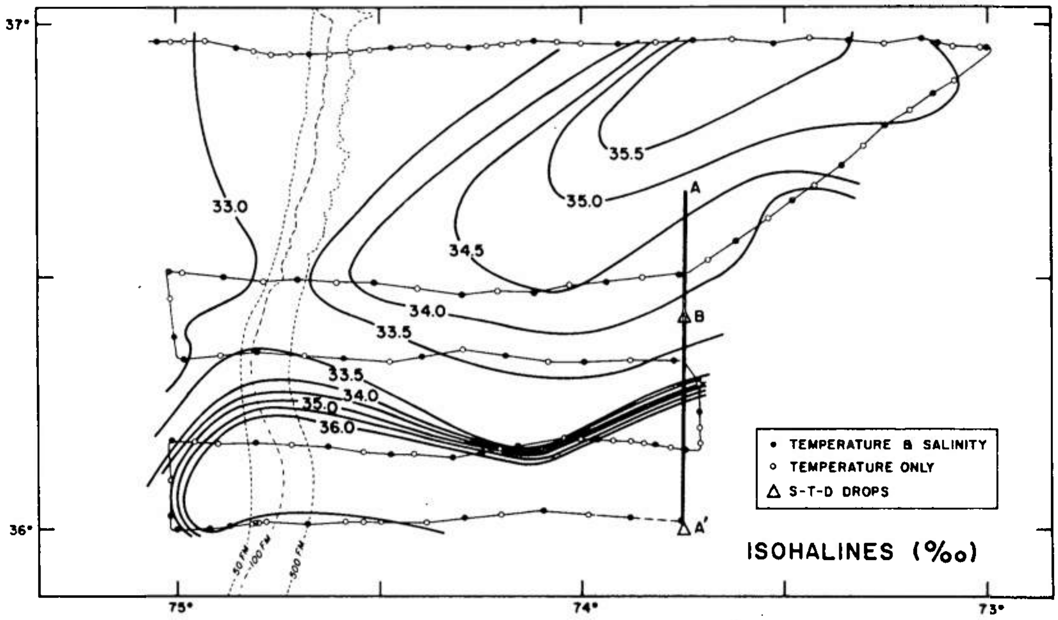

Figure 22 Surface salinity, 11-13 May 1969

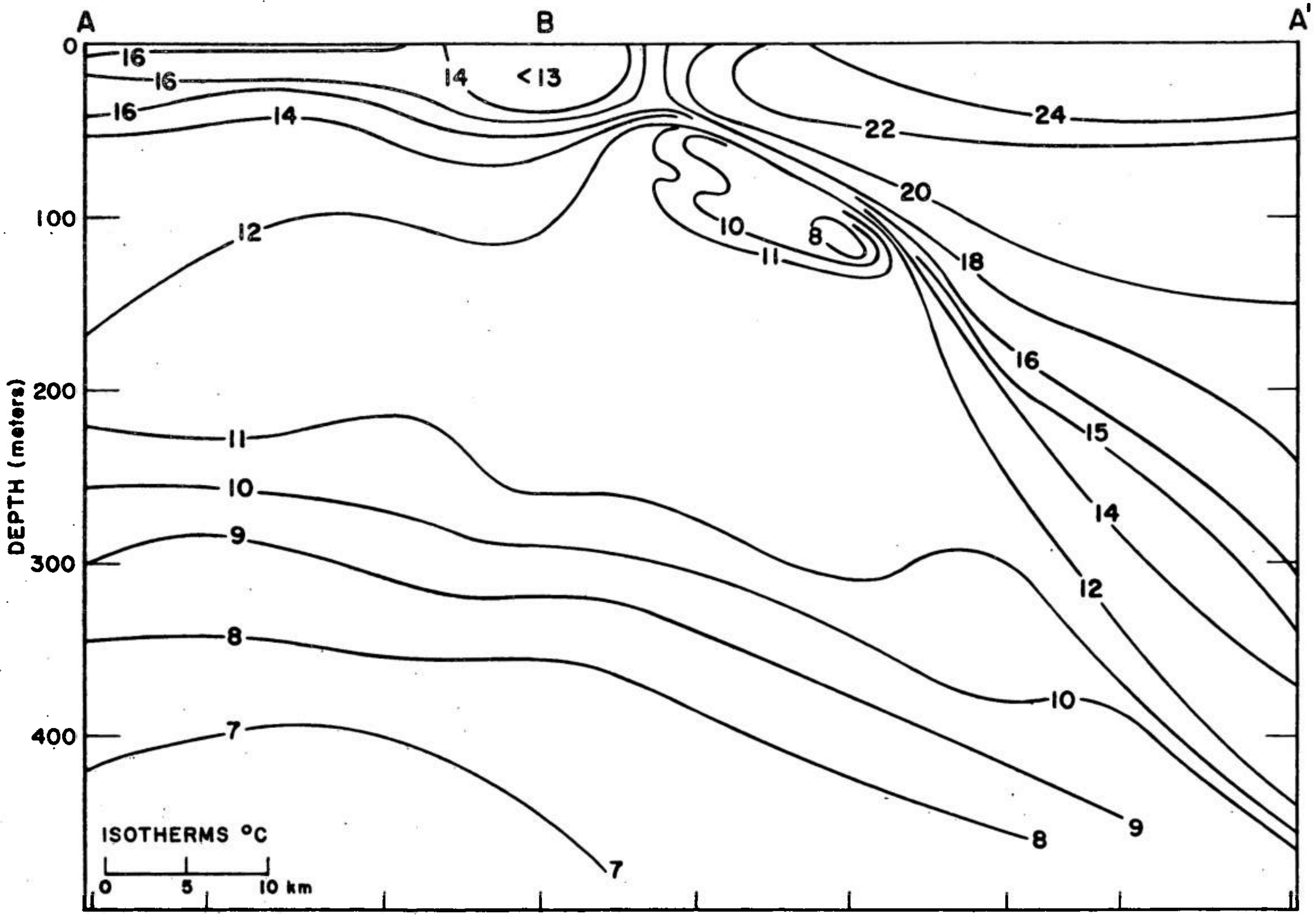

Figure 23 Temperature section, 13 May 1969

Complex temperature inversions frequently observed along the northern edge appear to be similar to the surface filament in that (1) thermohaline characteristics imply origin in Shelf Water and (2) they are discontinuous. An example of an inversion adjacent to the northern edge appears in figure 23, which shows 8°C water at the same depth (118 m) as 12°C in Slope Water and 20°C in the Gulf Stream. Data are insufficient to reliably determine temporal and spatial variation of the inversions, but the resulting strong sound channels have been observed during all seasons. Particularly strong inversions occur on the upstream side of meanders and beneath areas of overrunning.

B. Slope Front

The frontal zone separating Shelf Water from Slope Water frequently coincides with the Continental Slope, hence the term slope front (figure 24). The thermal gradient across the front is minimal in summer, when maximum solar radiation raises the temperature of Shelf Water to near that of Slope Water. During this period the slope front is undetectable from surface temperature measurements. The maximum thermal gradient across the front (less than 1.0°C/km) is observed in late winter when minimum SST occurs in Shelf Water.

The salinity gradient across the front is directly related to the influx of river runoff. Thus, the salinity gradient is greatest when maximum runoff from spring rainfall and meltwater has been mixed throughout the shelf area and smallest when minimum runoff occurs. The larger volume of Shelf Water in summer may also change the position of the slope front. On the average,however, the 34.0 and 35.0 °/oo isohalines will coincide with the shelf break seaward of the Chesapeake Bay.

Variations in the location of the slope front frequently occur in the form of (1) meanders similar to those observed along the northern edge and (2) overrunning of Slope Water by Shelf Water. An example of slope front meanders is shown in figure 25. (The front is delineated here by the 16° and 19°C isotherms.) Wavelength and amplitude of the meanders are 80 km and 15 km, respectively.

An example of overrunning of Slope Water by Shelf Water is shown in figure 26, in which Shelf Water occurs some 120 km offshore of the 200 m isobath. Expendable bathythermographs dropped in the area within 2 days of the ART observations show a layer of cold Shelf Water about 100 meters thick overlying Slope Water. Cold water overlying warm water is unstable, and the layer would be quickly destroyed through mixing if the surface water were not of lower salinity (less dense) than the underlying water. Bathythermograph traces representative of slope front overrunning in winter and spring are shown in figure 9. Summer and autumn traces are omitted from figure 9 because overrunning cannot be determined from temperature measurements during these periods.

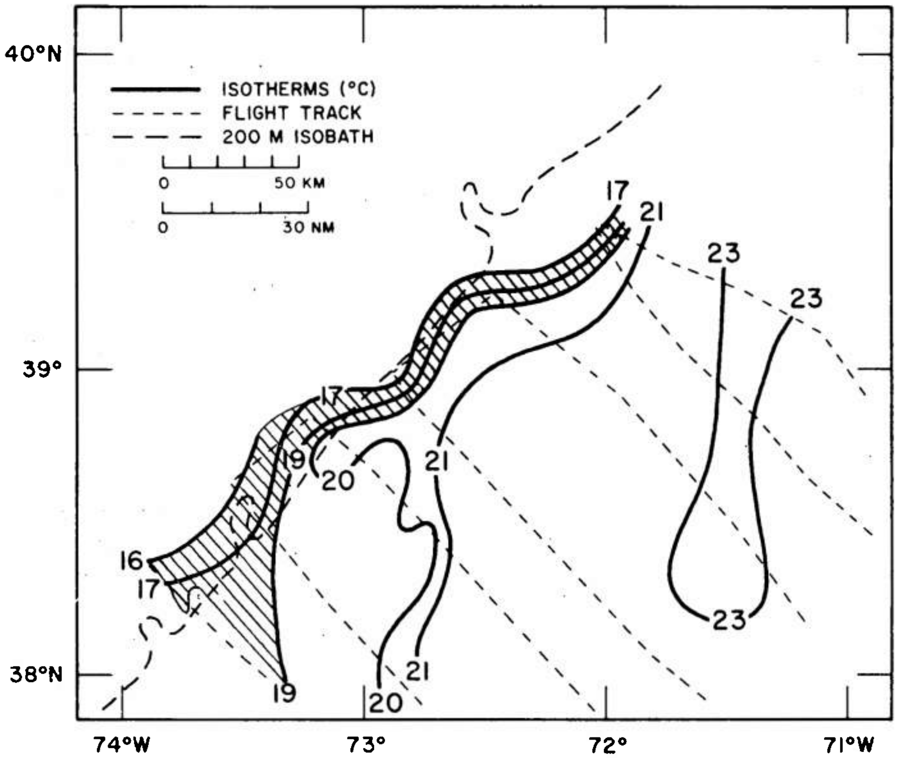

Figure 24 Slope front, 12 November 1969

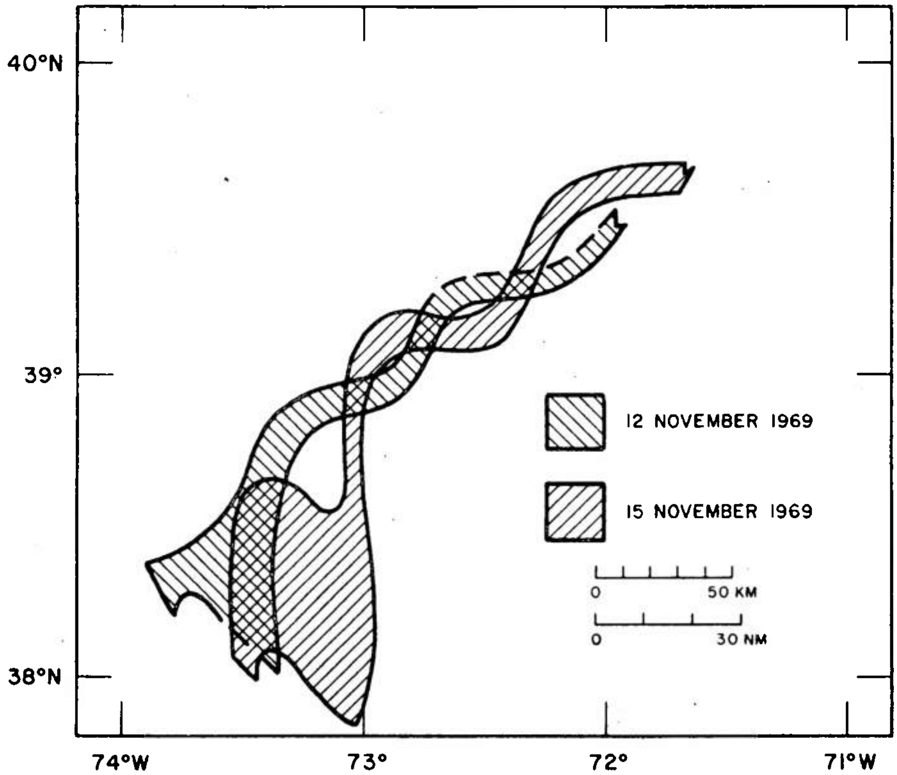

Figure 25 Slope front meander

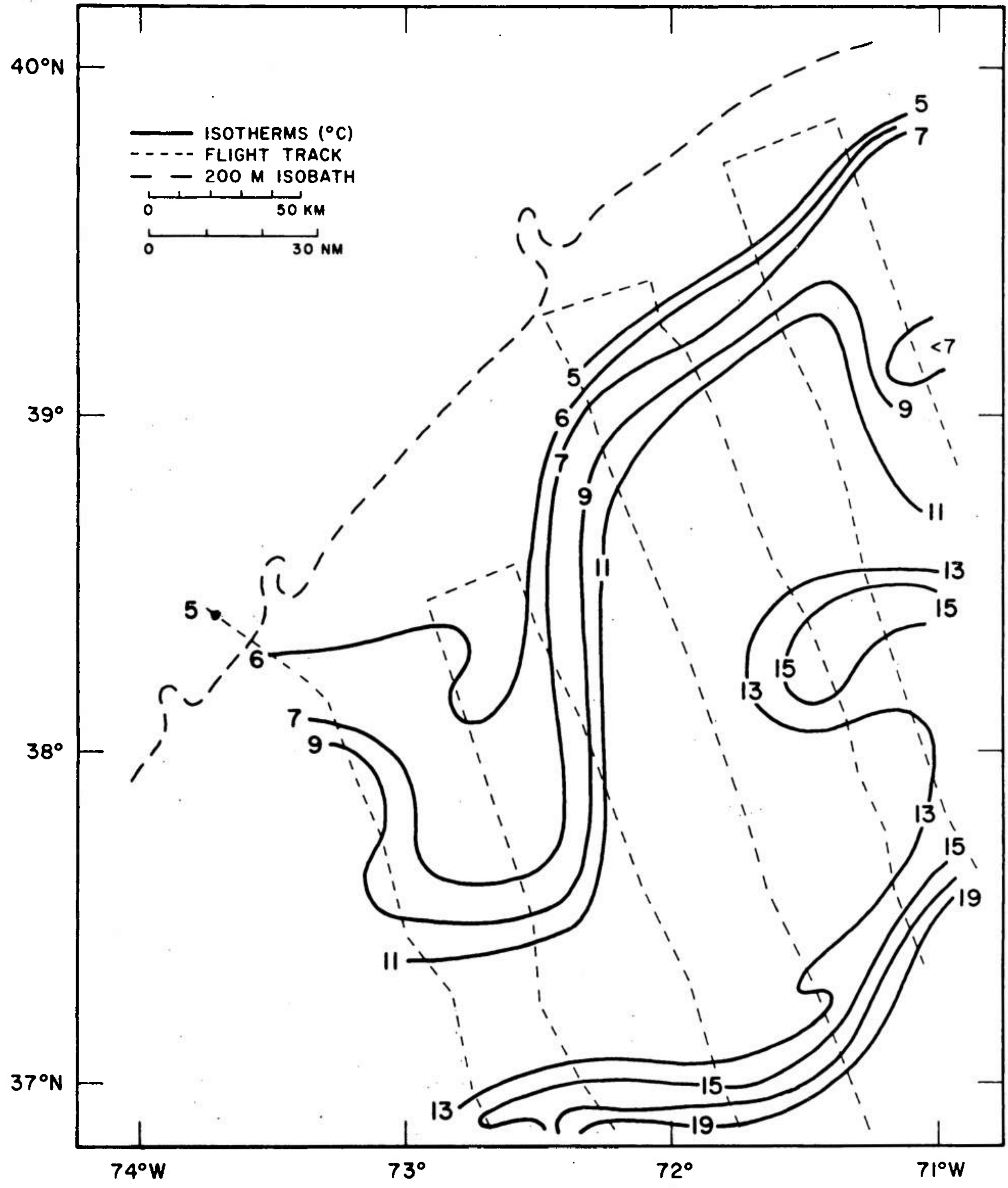

Figure 26 Shelf Water overrunning Slope Water, 14 March 1970

During summer, when surface heating precludes detection of the front from surface temperature observations, the slope front is marked by a temperature inversion near the shelf break. This inversion, which forms a strong sound channel extending from Cape Cod to Cape Hatteras, is explained by Cresswell (1967) in the following manner:

(1) The supply of Shelf Water in spring is greater than the volume over the Continental Shelf, with the result that cold Shelf Water protrudes seaward of the Continental Slope and overruns warm Slope Water.

(2) Increased vernal heating forms the seasonal thermocline, resulting in a cold layer between 2 warm layers.

(3) Salinity in the near-surface layer (including the thermocline and the underlying cold water) is sufficiently low to maintain a stable water column.

(4) The inversion persists until midautumn, when a combination of diffusion and autumnal overturning destroys the inversion.

(5) The diffusion process is aided by cold bubbles breaking away from the inversion (similar to calving of icebergs from a glacier) and drifting seaward.

Seasonal variation in strength of the slope inversion is illustrated by four temperature profiles taken near 37°N between 73°W and 75°W (figure 27). The winter (January) profile shows a strong gradient (9°-13°C, about 0.6°C/km) at the slope front and no indication of an inversion. Four months later, in spring (May), a well-defined inversion is present but the slope front is no longer evident at the surface. Minimum temperature (5.5°C) is well below minimum temperature observed on the shelf in January thus indicating the severity of cooling which occurred during late winter. Continued heating of the surface layer eliminates all near-surface features by late summer (September), but the inversion persists despite obvious weakening. Overturning destroys the seasonal thermocline and the inversion by late autumn (December). The slope front has been reestablished but is weak.

Table 2 summarizes the thermal characteristics of the slope front and the northern edge of the Gulf Stream.

C. Other Fronts

The Gulf Stream follows the Continental Slope northward and moves offshore east of Cape Hatteras. Shelf Water generally is not observed south of Cape Hatteras, but is common north of the Cape at all times. On occasion, however, Slope Water moves southward past the Cape beneath a surface layer of Gulf Stream Water. Therefore, Gulf Stream Water comes

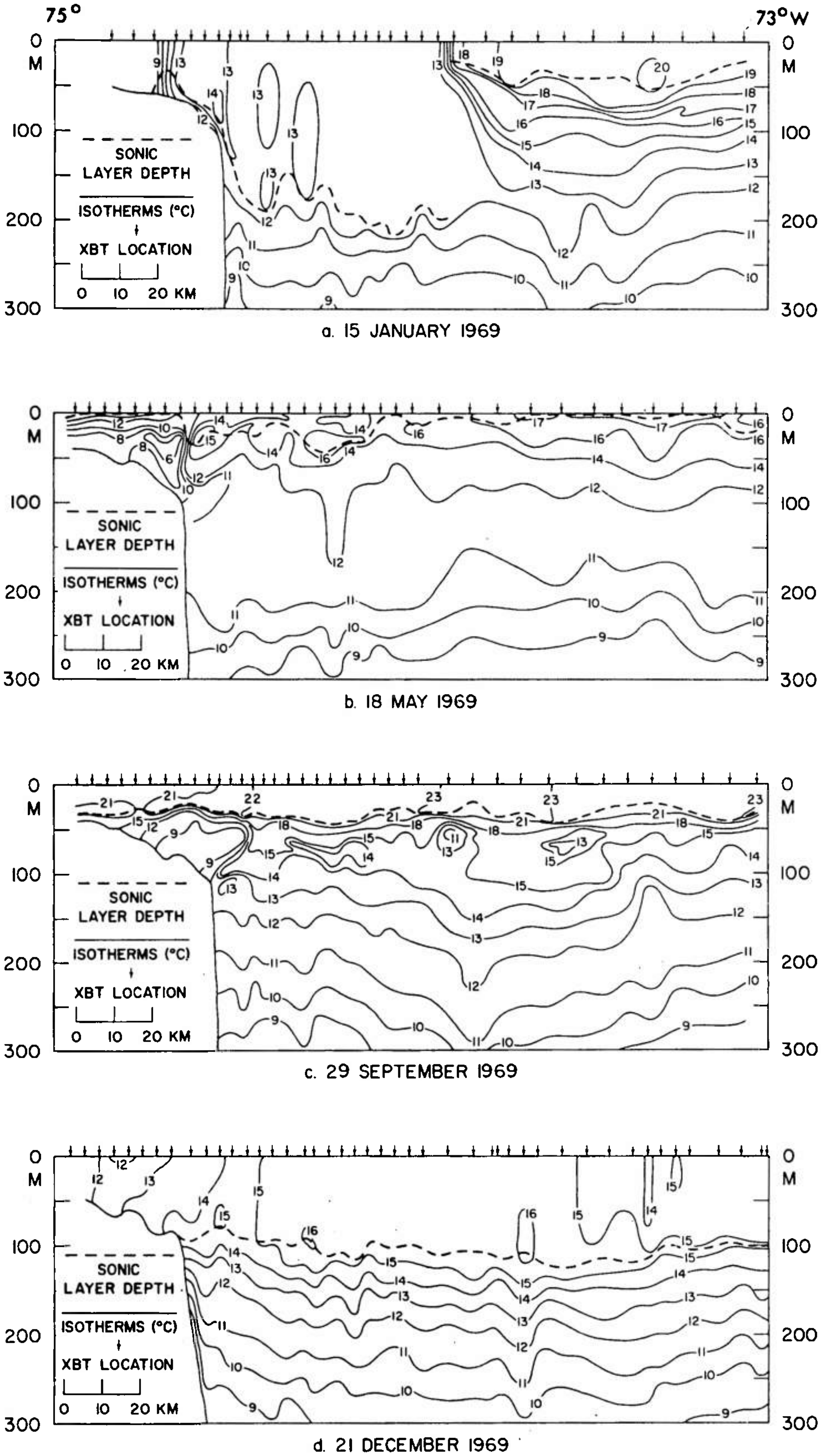

Figure 27 Seasonal temperature sections across the slope front

TABLE 2 THERMAL FRONTAL CHARACTERISTICS

Season	Slope Front	Northern Edge of Gulf Stream
Winter	a. Mean temperature change across front is 5.0°C. b. Gradient across front at annual maximum. c. Considerable overrunning of Slope Water by Shelf Water. d. Sound channels observed infrequently.	a. Mean temperature change across front is 6.2°C.* b. Gradient across front at annual maximum. c. Multiple gradients occur frequently (54 percent). d. Strong sound channels observed. e. Considerable overrunning of Slope Water by Stream Water.
Spring	a. Surface heating reduces temperature change and gradient across front. b. Front moves offshore. c. Strong sound channels form along Continental Slope.	a. Mean temperature change across front is 5.3°C.* b. Surface heating reduces temperature change and gradient across front. c. Overrunning and sound channels frequent.
Summer	a. Thermal front not discernible at surface. b. Front delineated by strong sound channels.	a. Mean temperature change across front is 2.4°C.* b. Gradient across front at annual minimum. c. Multiple gradients observed less frequently than in other seasons (25 percent). d. Overrunning and sound channels frequent.
Autumn	a. Thermal front reestablished by surface cooling. b. Sound channels destroyed by overturning.	a. Mean temperature change across front is 4.4°C.* b. Gradient across front intensifies. c. Sound channels and overrunning frequent.

*Adjusted from data given by Bratnick and Kerling into contact with Shelf Water at the surface near Cape Hatteras. These fronts are limited in extent and somewhat temporary in nature. The horizontal thermal gradient can be steep, however, as shown by figure 28.

V. SPECIAL FEATURES

A. Sound Channels

Sound channels occur frequently in the VACAPES area with useful sound channels caused by different phenomena often observed close to one another. Sound channels observed during May 1970 (figure 29) provide an excellent illustration of such an occurrence. The strong sound channels delineated result from: (1) mixing between water masses along the slope front (BT A), along the northern edge (BT B), and at the boundary of an area of warm overrunning (BT C); (2) surface heating in Slope Water (BT D) and where Shelf Water has overrun Slope Water (BT E); and (3) a thick layer of near-isothermal water (depressed sound channel) typical of Sargasso Sea Water (BT F). Although Sargasso Water is not a subject of this report, BT F is shown for comparison.

Strong sound channels are often observed below entrained water and below the overrun waters adjacent to the northern edge.

B. Eddies

Major frontal perturbations, such as meanders, cause both cold and warm eddies. In the Gulf Stream, cold eddies are formed south of the stream when a tongue of Slope Water is cut off by a meander moving downstream. The resulting cyclonic eddy will then drift into the Sargasso Sea. Warm, anticyclonic eddies are formed when a Gulf Stream meander becomes unstable, breaks off from the stream, and drifts into Slope Water. Smaller subsurface water parcels, which break off from the temperature inversion associated with the slope front, are not classified as eddies because they apparently are caused by tidal agitation and the breaking of internal waves and thus do not have a well-defined current system. Cold eddies generally are observed to the east of the VACAPES area and will not be discussed here.

Warm, anticyclonic eddies have been reported less frequently than cold eddies. Progression of such an eddy between 4 November 1970 and 4 January 1971 is shown in figure 30. The broken arrow indicates only that the eddy originated in the Gulf Stream and does not necessarily indicate actual drift. Rate of drift was 5.7 km/day between 5 November and 9 December and increased to 10.3 km/day between 9 and 23 December, before decreasing to 7.1 km/day prior to reentering the Gulf Stream system on 4 January. A comparison of SST on 9 December (figure 31) with temperature at the 200-m level (figure 32) shows that the eddy is less distinct at the surface because of cooling and mixing in the near-surface layer.

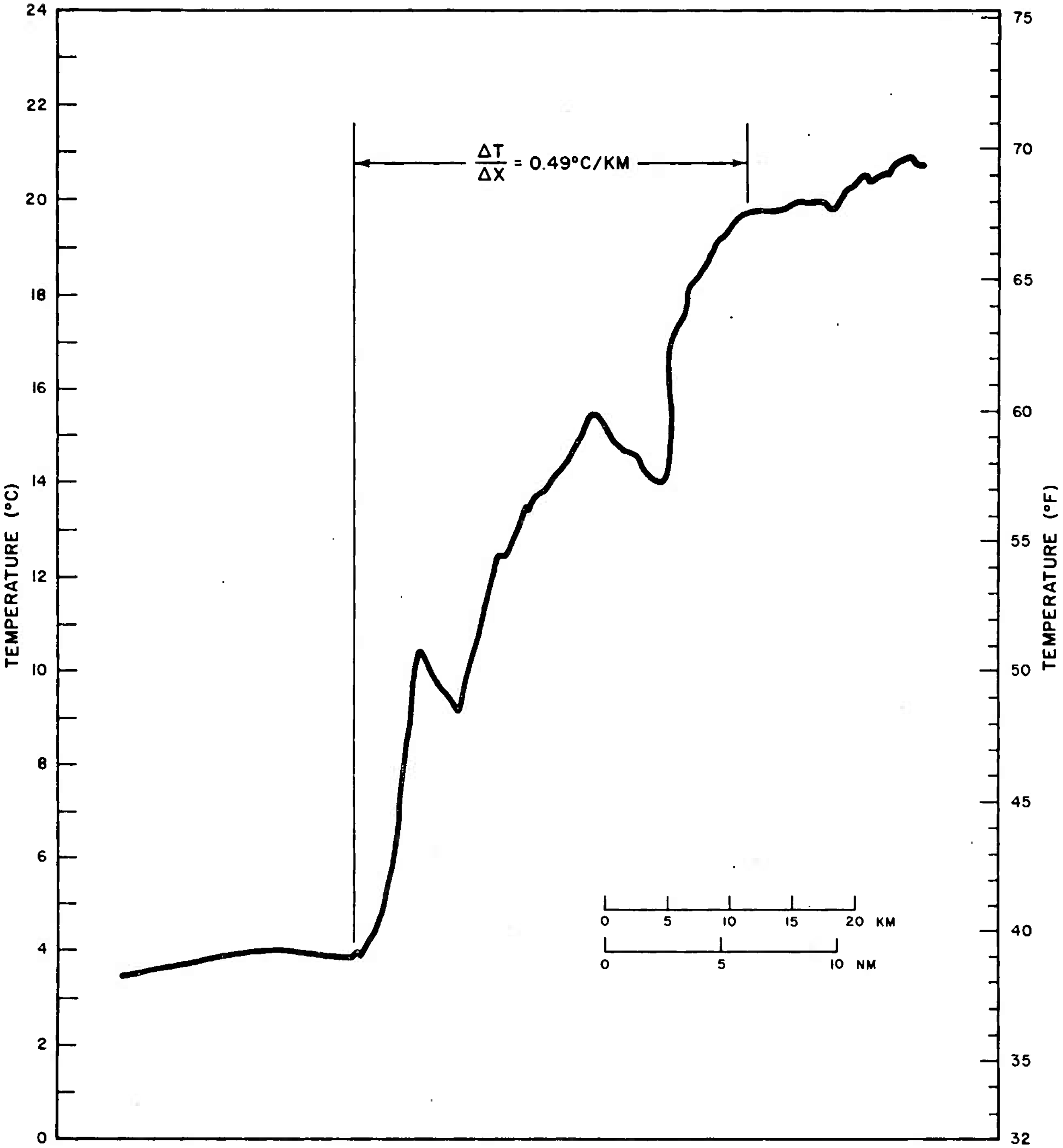

Figure 28. Northern edge seaward of Cape Hatteras, 5 February 1969

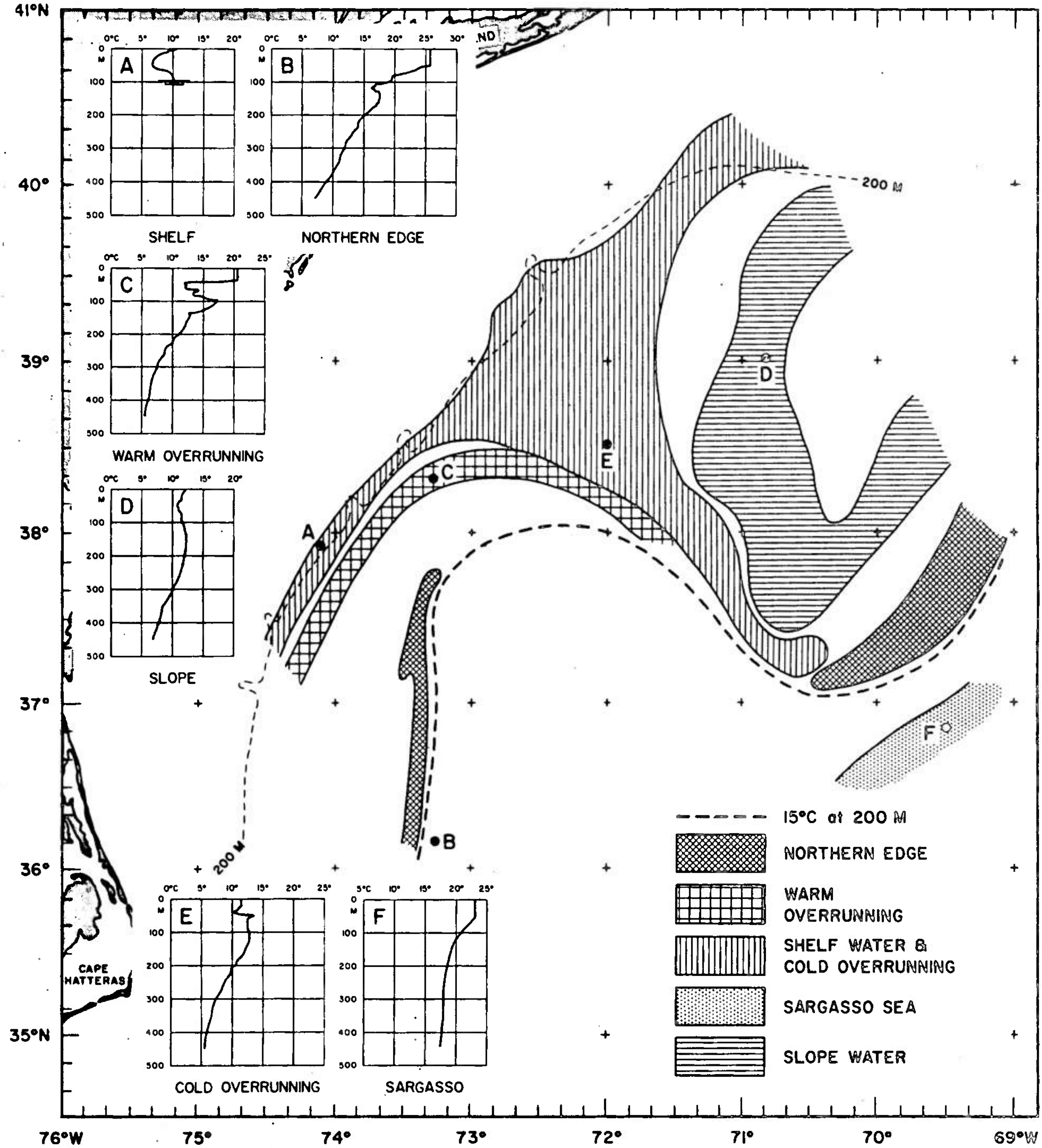

Figure 29 Distribution of strong sound channels, 15–21 May 1970

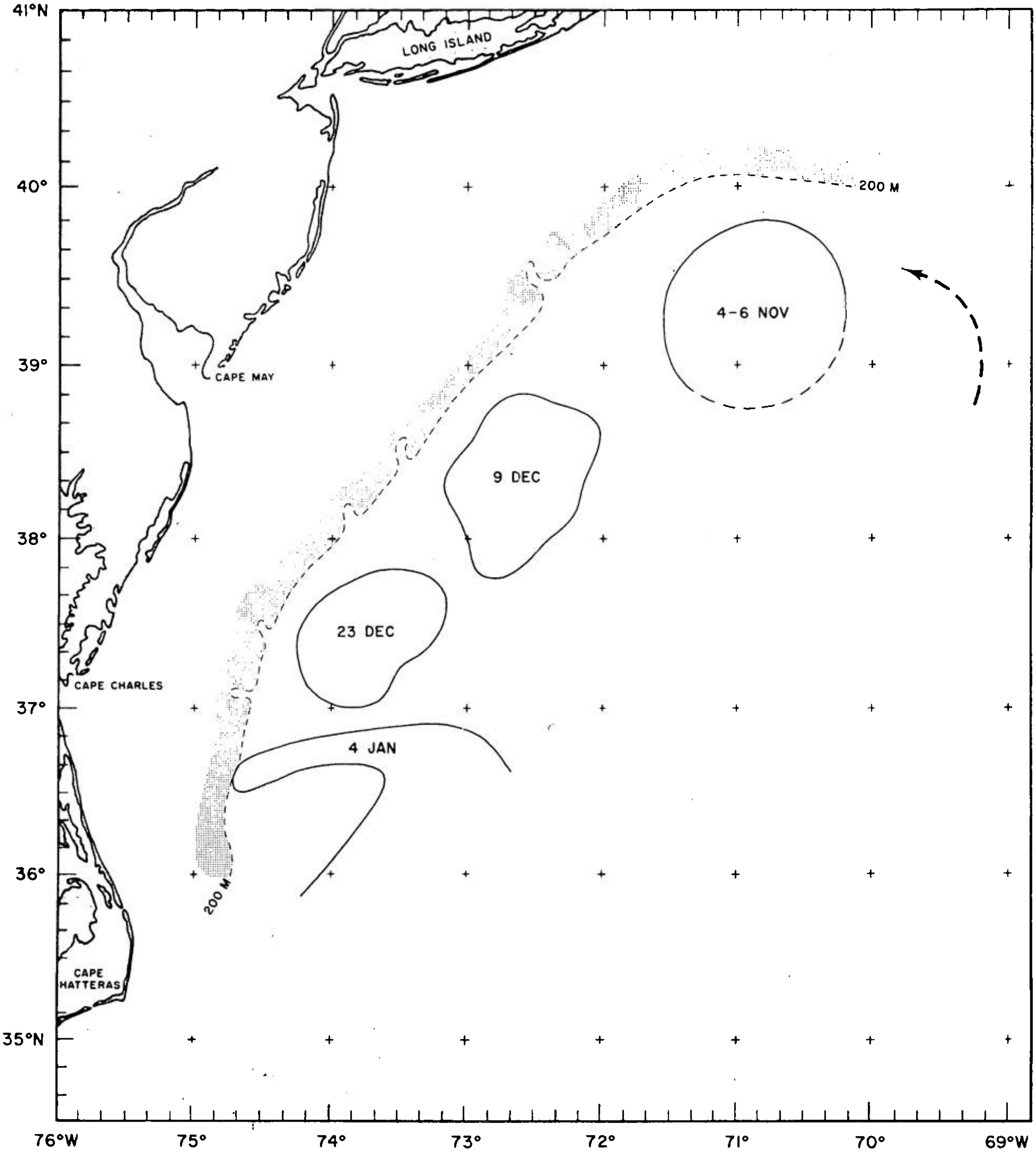

Figure 30 Progression of warm eddy, November 1970 to January 1971

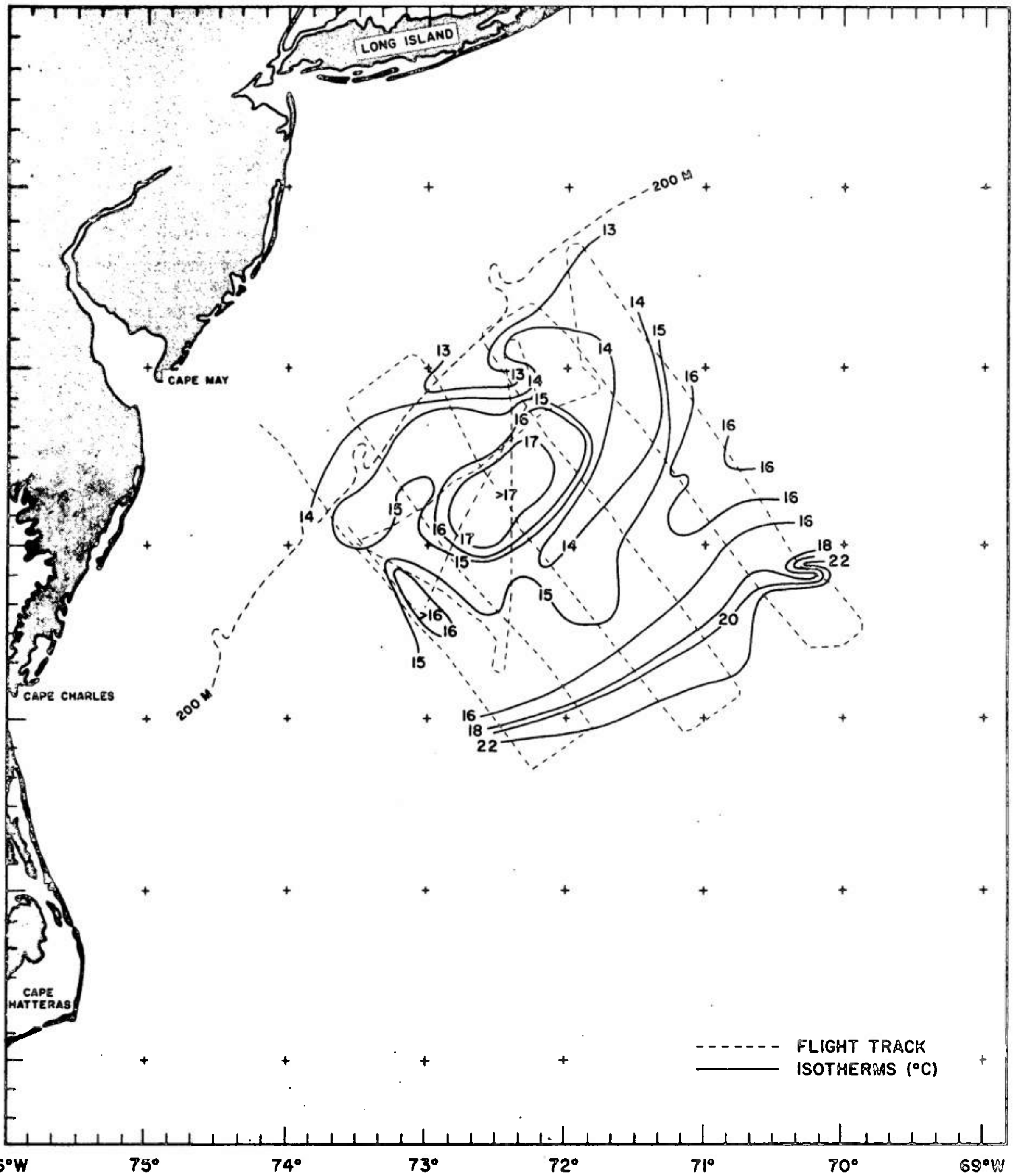

Figure 31 Sea surface temperature, warm eddy, 9 December 1971

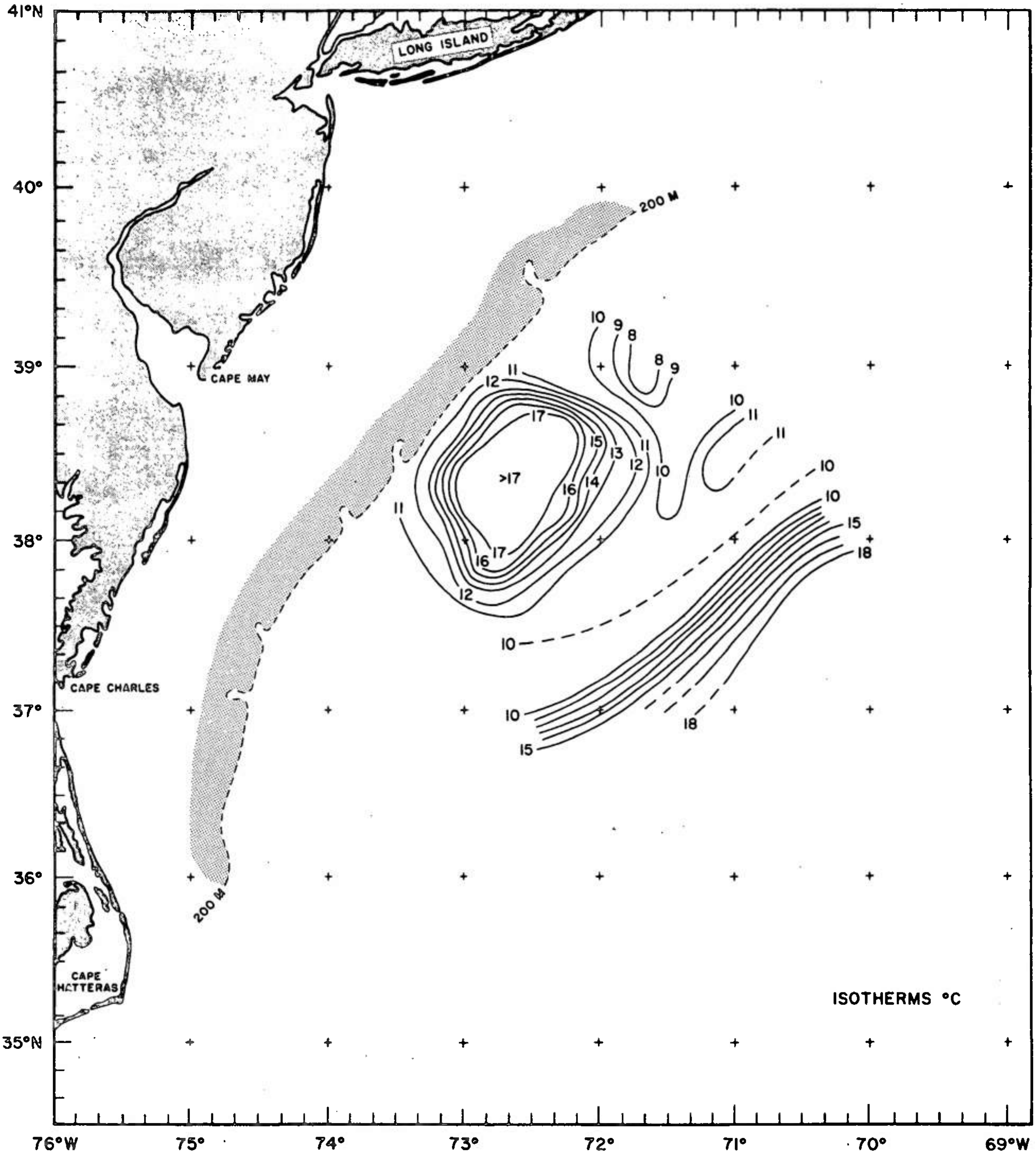

Figure 32 Temperature at 200 meters, warm eddy, 9 December 1971

Divergence, in the form of upwelling, is evident by cold water at both levels upstream (north) of the eddy. Surface salinity samples taken in, and adjacent to, the eddy on 13 and 13 December show values greater than 34.8 $^{o}/oo$ outside the eddy. Salinity-Temperature-Depth (STD) casts show that the eddy is discernible at the 1,500-m level.

C. Currents

There are few current measurements in the VACAPES area; most circulation diagrams are deduced from random ship drift reports. Because ship fixes are often inaccurate and infrequent, the resulting current calculations are questionable. Such values are more typical of means and unlikely to show extreme values or narrow jets of moving water. Figure 33 illustrates the generally accepted current pattern in the area, but this may be modified temporarily by the action of winds. Strong winds, or even moderate winds of a persistent duration, produce wind drift currents, cause convergence or divergence of water along the coast, and confuse the local circulation. Strong northeast winds, for instance, produce a south-setting longshore circulation.

Current measurements in the Gulf Stream show a narrow, high-velocity core located between the northern edge and the high-temperature core. Measurements with a geomagnetic electrokinetograph (GEK) show peak surface currents in the high-velocity core as great as 274 cm/sec,with velocities greater than 200 cm/sec common (Von Arx, 1950). Geostrophic calculations show estimated currents of 100 cm/sec at 400 m and measurements with Swallow floats indicate currents of 11 cm/sec near 2,500 m (Warren and Volkmann, 1968).

Few near-surface current data are available for Slope Water. Historical drift observations computed for 1-degree squares frequently are misleading because of unequal areal distribution of data. Drift cards also are misleading in that they reflect current in the upper few centimeters, which are heavily influenced by the wind. Basically, a southerly drift occurs, except near Cape Hatteras, where the current sweeps seaward, and inshore of the Gulf Stream, where northeasterly drift occurs. Thus, the circulation is basically anticyclonic. Variation in this flow will occur when eastward advection of Shelf Water occurs. Deep currents of 10 to 22 cm/sec have been measured at 2,000 m in Slope Water south of Cape Cod with free-floating buoys and parachute drogues (Volkmann, 1962).

Southwesterly currents predominate on the Continental Shelf, except in summer when southerly winds subsequent to periods of low rainfall may cause northerly currents (Bumpus, 1969). Little or no Shelf Water is transported south of Cape Hatteras at the surface except during periods of sustained northeasterly winter winds. Therefore, a seaward sweep of Shelf Water can be expected in this area perhaps as a cold entrainment by the Gulf Stream (Fisher and Gotthardt, 1970).

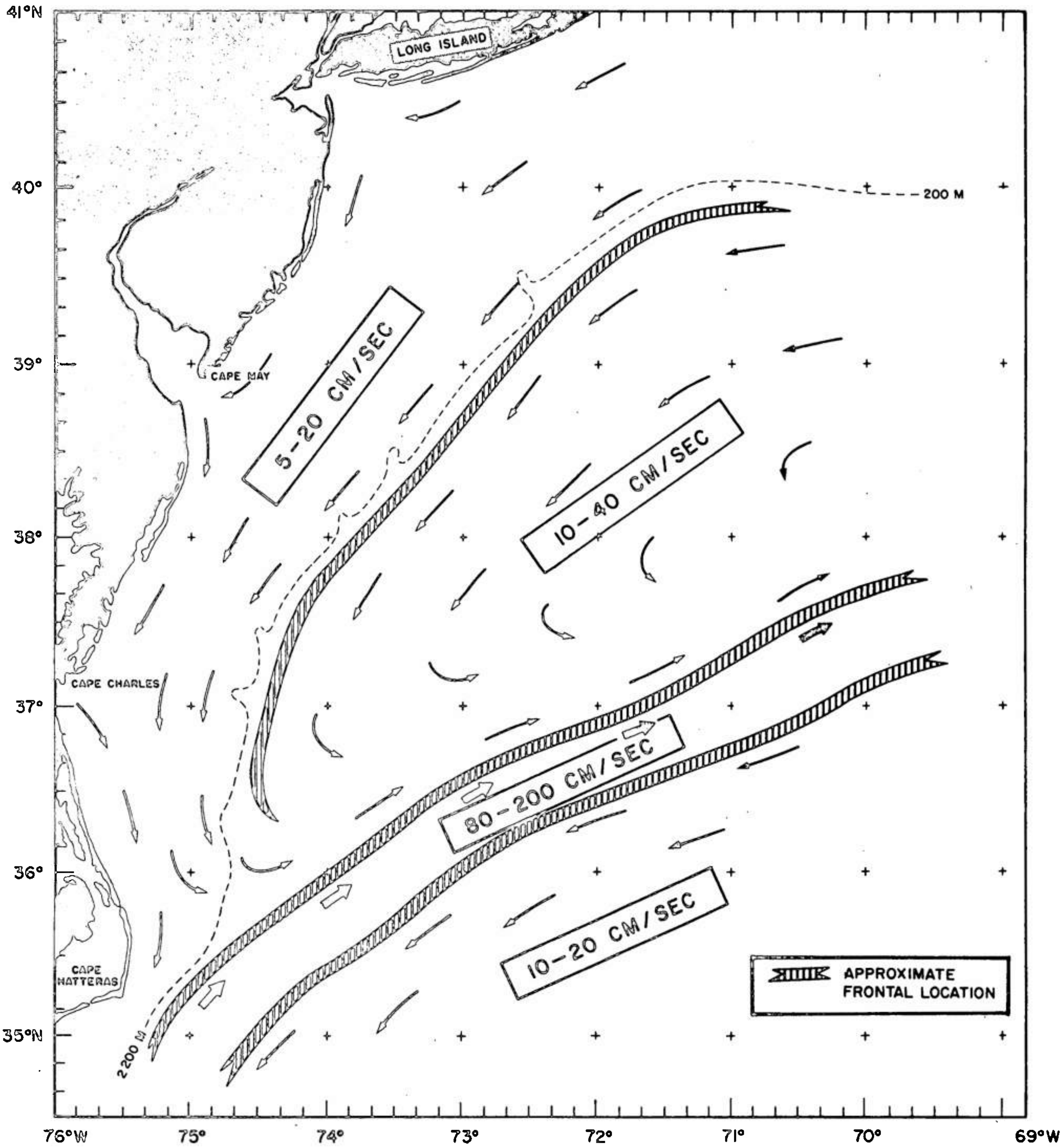

Figure 33 General surface circulation, VACAPES area

D. Waves

Waves are a transitory phenomenon; therefore, wave conditions in the VACAPES area cannot be described in specific terms of where and when. Highest waves occur in winter storms which form off Cape Hatteras and move northeastward through the VACAPES area. Waves in excess of 10 m are possible in these storms, although heights of 5-7 m are more common.

There is little swell in the area owing to the offshore movement of storms and the orientation of strongest winds in distant storms to the east. An exception to this occurs when hurricanes or tropical disturbances move northward off the coast and propagate east to southeasterly swell into the VACAPES area.

Waves form as a function of wind strength, wind duration, and distance over which the wind blows (fetch). As a result, the waves are lower in summer than winter, owing to lighter winds. They are also higher in the eastern sector of VACAPES area, because all offshore winds create a gradient of wave heights increasing seaward. Waves are increased in steepness and height by a conflicting current; consequently, easterly waves can become very rough as one enters the Gulf Stream circulation. Owing to the complexity of the circulation patterns in VACAPES it is possible to encounter this problem anywhere in the area.

A cumulative frequency of wave heights by seasons is shown in figure 34. Maximum and minimum wave heights occur respectively in winter (50 percent of observations greater than 0.8 m, 95 percent less than 3.1 m) and summer (50 percent greater than 0.3 m, 95 percent less than 2.1 m).

E. Biology

This section discusses possible biological false targets in the area. The VACAPES area contains marine life ranging from microscopic plankton to large whales. Their abundance and distribution are strongly influenced by environmental factors, which divide the area into distinct ecological regimes. Shore fishes and neritic invertebrates occupy the waters over the shelf. Among fishes found here are croakers, sea robins, sea bass, sharks, rays, bluefish, alewives, and menhaden; invertebrates include clams, scallops, crabs, jellyfish, and copepods. The Slope Water environment supports numerous large pelagic fishes, such as tuna, marlin, swordfish, and sailfish as well as haddock and hake. Whales and porpoises are present in this area. The Gulf Stream transports many warm-water organisms northward and serves as a barrier to certain cold temperature forms. Dolphins, jacks, and triggerfish may occur in the warm stream, but tuna, billfish, and most species of porpoises and whales prefer the cold side of the Gulf Stream northern edge.

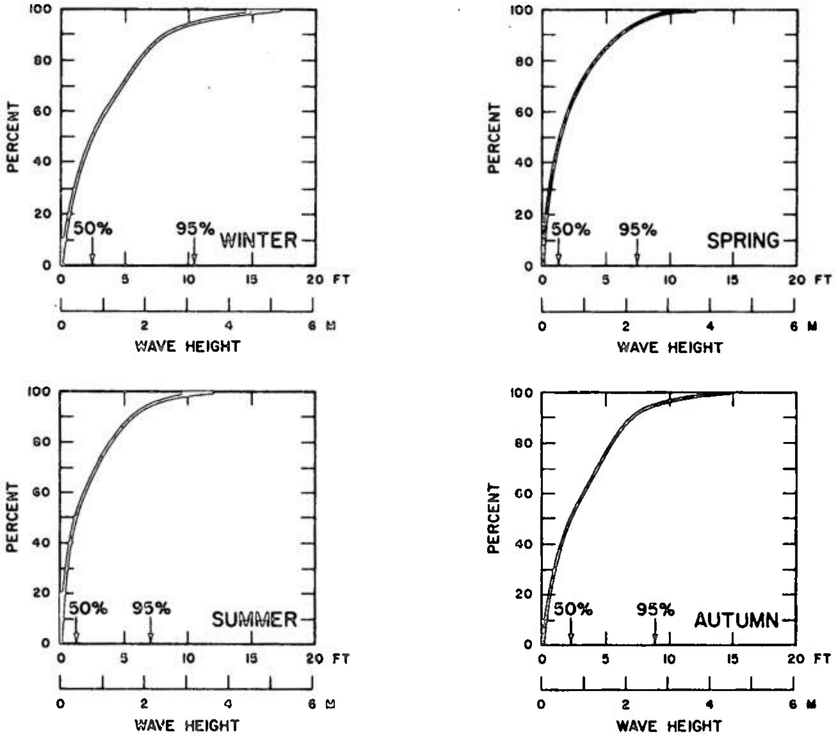

Figure 34 Seasonal wave height

Whales are the most likely false targets and are most frequent in the area during July and August. The numbers of whales per 1,000 square kilometers in Shelf, Slope, and Gulf Stream waters are shown in table 3. The largest concentrations appear between the Continental Slope and the northern edge of the Gulf Stream. These concentrations usually increase from west to east during all months and decrease from summer to winter.

TABLE 3 DISTRIBUTION OF WHALES

Month	Shelf Water	Slope and Gulf Stream Water
January	1 (whales/1000 km^2)	0-1
February	3	3-4
March	1	1-3
April	2	2-3
May	4	4-5
June	4	4-11
July	4	4-7
August	4	4-5
September	1	1-4
October	1	1-4
November	1	1-4
December	1	1-3

There are no reliable statistics describing numbers of schooling and large pelagic fishes. Most schooling fishes leave Shelf Water in winter and move into deeper water. The large pelagic forms such as tuna, billfish, and bluefish migrate seasonally, occurring in greatest abundance along the Gulf Stream boundary in spring and autumn.

Porpoises follow the same general distribution as the larger whales, except that they also occur in Shelf Water in rather large numbers.

Sharks occur throughout the area with large concentrations in Shelf Water and near the shelf break. An exception is the hammerhead shark which appears only in Gulf Stream Water during winter months. This species generally prefers water temperatures greater than 19°C.

Volume reverberation (scattering) is variable in the VACAPES area. Echo sounder records show considerable scattering in Shelf and Slope Waters but less in Gulf Stream Water. An increase in scattering was observed near frontal zones.

Diurnal and seasonal variation in volume reverberation occurs. Signal to interference ratio of surface duct mode sound propagation decreases at night, owing to the increased volume reverberation in the near surface layer. In the VACAPES area swimbladder-bearing mesopelagic fish, such as the bristlemouth, hatchetfish, and lanternfish, probably are the primary sources of volume reverberation. Seasonal abundance of marine organisms during the spring and autumn plankton blooms is expected to increase volume reverberation.

Ambient noise in the VACAPES area may be either biological or nonbiological in origin. Biological sources (snapping shrimp, croakers, sea robins) contribute at all frequencies in shallow water and may be the dominant noise source for limited periods in localized areas. Large whales in deep water are suspected contributors to the ambient noise level at frequencies below 1 kHz during their migration through the area. All biological noise is characterized by short duration, frequent repetition, and wide variety of sound.

Wenz (1962) has shown that nonbiological sources of ambient noise are affected by a combination of three spectra: wind-dependent (50 Hz to 10 kHz), nonwind-dependent (10 Hz to 1 kHz), and low-frequency (1 to 100 Hz). Maximum overlapping of these spectra occurs in the 10-Hz to 1-kHz-frequency band. Distant shipping is the dominant ambient noise source at frequencies below 0.5 kHz, whereas wind-dependent ambient noise is dominant above that level. For the same wind-speed, a 5-db increase in wind-dependent noise was observed in shallow water areas.

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Appendix

Sound Channel
Classification

SOUND CHANNEL CLASSIFICATION

Classification of near surface sound channel strength used in this paper is based upon a method developed by Anderson (1967)* in which depth of sound channel axis, channel thickness, and maximum angle of sonic rays trapped within the channel are used to estimate performance of active Fleet sonar. Although this method neither considers sonar frequency nor has been operationally evaluated, it provides a reasonable technique for estimating sound channel strength.

The sound channel axis is the sound velocity minimum within the layer; the layer midpoint is the sound channel axis in cases of isovelocity layers. Channel thickness is determined from depths of sound velocity maxima above and below the axis. The lesser of the two sound velocity maxima determines the depth of one channel boundary; and the second boundary is the depth of equal sound velocity on the opposite side of the axis. Maximum angle of sonar rays trapped in the sound channel (assuming transducer position in the axis) is given by:

$$\theta = \text{arc cos } (V_o/V_1)$$

where V_o is sound speed at the sound channel axis and V_1 is sound speed at the sound channel boundaries.

Strength of the sound channel (S) is determined by adjusting θ to reflect layer thickness (ΔZ) and dividing by 100 ft-deg to provide dimensionless, low valued results:

$$S = \Delta Z \times \theta \times 10^{-2} ft^{-1} deg^{-1}$$

The metric equivalent of the above equation is:

$$S = 3.28 \times 10^{-2} \times \Delta Z \times \theta \; m^{-1} deg^{-1}$$

Sound channels are subdivided into six groups based on strength:

None	$S = 0$
Very Weak	$0.1 \leq S < 3.0$
Weak	$3.0 \leq S < 5.0$
Moderate	$5.0 \leq S < 8.0$
Strong	$8.0 \leq S < 20.0$
Very Strong	$S \geq 20.0$

*Anderson, R. W. (1967) "Analysis and prediction of shallow sound channels," Presented at the Second NATO Military Oceanographic Seminar, Hamburg, Germany, 14p.

Sound channels are estimated to be useful for Fleet ASW operations when: (1) axis depth is greater than 15 meters and less than 200 meters, (2) thickness is 15 meters or more, (3) maximum angle trapped is 2 or more degrees, and (4) S is 5 or greater.

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13. ABSTRACT The general oceanography of the Virginia Capes (VACAPES) area is discussed with particular emphasis on near-surface thermal structure of water masses and oceanic fronts. Warm, saline Gulf Stream Water, identified by temperature equal to or greater than 15°Celsius (C) at the 200-meter (m) level, is characterized by mean monthly sea surface temperature (SST) and sonic layer depth (SLD) ranging from 21°C and 78m, respectively, in winter to 28°C and 25m in summer. Slope Water, identified by temperatures between 9° and 15°C at the 200-m level, is characterized by a temperature inversion in spring and mean monthly SST and SLD ranging from 11°C and 203m, respectively, in winter to 25°C and 6m in summer. Relatively fresh Shelf Water, found on the Continental Shelf between the 30-m and 200-m isobaths, is characterized by a positive in-layer temperature gradient in winter and mean monthly SST ranging from 7°C in winter to 25°C in summer. SLD is at the bottom in winter and is 3m in summer. Two major oceanic fronts occur in the VACAPES area: the northern edge of the Gulf Stream separating Gulf Stream Water from Slope Water and the slope front separating Shelf Water from Slope Water. The northern edge is characterized by mean seasonal temperature differences across the front ranging from 6°C in winter to 2°C in summer, frequent cold filaments and multiple temperature gradients at the surface, and temperature inversions throughout the year. The slope front is characterized by a mean seasonal temperature difference across the front ranging from 5°C in winter to nil in summer (when surface heating masks the front) and a well-formed temperature gradient from spring through autumn. Water mass interaction, in the form of Gulf Stream meanders, eddies of Gulf Stream origin in Slope Water and entrainment of Shelf Water by the Gulf Stream cause the area to be complex oceanographically.

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Oceanographic Prediction						
Oceanography						
Physical Properties						
Salinity						
Sea Water						
Shallow Water						
Temperature						
Virginia Capes						
Eddies						
Meanders						
Sound Channels						
Entrainment						

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1. Oceanography. 2. Thermohaline prediction. 3. Virginia Capes - Operating Area. 4. North Atlantic. I. Title. II. Fisher, Alvan, Jr., auth. III. Special Publication No. 211.

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